RADC-TDR-64-201
Final Report

INVESTIGATION OF TECHNIQUES FOR SPACE-ORIENTED TUBES

TECHNICAL DOCUMENTARY REPORT NO. RADC-TDR-64-201

September 1964

Techniques Branch
Rome Air Development Center
Research and Technology Division
Air Force Systems Command
Griffiss Air Force Base, New York

Project No. 5573 , Task No. 557303

(Prepared under Contract No. AF 30(602)-2984 by the Bendix Corporation Research Laboratories Division, Southfield, Michigan. Authors: Dr. John G. Meeker, and A. G. Peifer.)

FOREWORD

Extensive use has been made of the vast amount of literature available on space experiments. In addition, specifications on testing of anticipated tubes published by cognizant government authorities have been reviewed.

In this quest it has also been possible to draw upon a considerable amount of recent experience, both experimental and theoretical, acquired by Bendix from similar programs. In obtaining information quoted in Sections 2 and 3, use has been made of reports and papers accumulated on previous and current in-house projects and programs, notably Space and Radiation Effects Project (RLD Project 7434 and its predecessors), and Bendix Extreme Environment Program (BEEP).

This study has been the joint effort of the Electron Beam and Tube Technology Department and of the New Technology Department of The Bendix Corporation, Research Laboratories Division. The contributing personnel and the subject matter of their contributions are listed below. To them appreciation is expressed.

New Technology Department - General Science and Technology Laboratory

Mrs. Ann Piken	Chapters 2 and 3 on the space environment and its effect on material
Mr. Frank W. Poblenz and Mr. B. G. Southward	Appendix A - An estimate of radiation exposure due to the Van Allen Belts
Mr. Carl Taulbee	Contributions to Chapter 5 on the philosophy and techniques for testing components and subassemblies.

Electron Beam and and Tube Technology Department - Applied Physics Laboratory

Miss Mary Schafer	Assembling and coordinating the material throughout the report
Dr. J. G. Meeker	Chapter 4 - Analysis of the problems and design goals for space tubes. Chapter 5 - The rise-to-orbit testing of electronic packages. Chapter 6 - Conclusions
Mr. A. G. Peifer	Chapter 6 - Many specific ideas on new concepts and recommendations.

Key Words: Microwave Amplifiers; Space Environment; Effects of Space Environment on Materials.

ABSTRACT

The primary goal of this study has been to establish criteria for designing high power microwave amplifiers capable of adequately functioning in environments associated with space missions.

The expected space environment, both natural and artificial, has been carefully catalogued and a special treatment for calculating the ionizing radiation of the Van Allen Belts developed, including assumptions and their degree of uncertainty. The effects of the over-all environment on the materials of a space tube package have been evaluated and the materials given a preference ranking. The essential properties required of a space tube are also enumerated and means of achieving them discussed, in detail, for linear-beam tubes, especially for traveling-wave amplifiers required to operate in the range between 1 Gc at 10,000 watts CW and 10 Gc at 100 watts CW. Limitations and problem areas are pointed out and some new concepts have been advanced.

The importance of pre-flight testing is emphasized, and a philosophy of combined-environment testing advanced; sequential testing is also discussed.

PUBLICATION REVIEW

This report has been reviewed and is approved. For further technical information on this project, contact R. Hunter Chilton, EMATE, Extension 4251.

Approved: R. Hunter Chilton
R. HUNTER CHILTON
Project Engineer
Electron Devices Section

Approved: Paul A. Baldwin
for Lt Col USAF
THOMAS S. BOND, JR
Colonel, USAF
Chief, Surveillance & Control Division

FOR THE COMMANDER: Irving J. Gabelman
IRVING J. GABELMAN
Chief, Advanced Studies Group

TABLE OF CONTENTS

Page

Page

Page

LIST OF ILLUSTRATIONS

SECTION 1

INTRODUCTION

1.1 OBJECTIVE

The primary goal of this study is to establish criteria for the design of microwave amplifiers and for the selection of their constituent materials that will allow the tubes to perform their functions adequately in the environmental conditions associated with space missions.

This final report concludes the study and covers the period from March 21, 1963 to March 21, 1964. It expands upon the interim report(1) published January 3, 1964 covering the first eight months of the period. Since the interim report was written, additional applicable literature has been found, of which several articles have been published as recently as April, 1964. These references have provided significant additional information concerned with micrometeorite hazards, solar flare advance warning, and a new radiation zone, which are discussed in Section 2 and radiation effects on ceramics, vacuum effects on dielectrics, and combined environmental effects on dielectrics, which are discussed in Section 3. Figures 3-2(a) and 3-2(b) have been added and additional data incorporated into Figures 2-5 and 2-6.

Section 4 which discusses the design of space tubes has been augmented to point out the limitations which bound the designs. Solutions are suggested for some of the problems critical to the space application, notably the beam collection problem. A state-of-the-art speculation for the next few years is also ventured and some new concepts advanced.

Recent information from new references concerning the rise-to-orbit stress profiles encountered by electronic payloads has been included in Section 5 on testing.

1.2 DEFINING THE SCOPE OF THE PROGRAM

The work is organized under three general headings: the space environment, tube materials, and the design of space-oriented microwave tubes.

1.2.1 Space Environment

The space environment is meant here to include all of the environmental stresses that an electron tube would be subjected to throughout its existence. These are the natural environments of space, the modified environment introduced by the presence of the satellite skin and the use of nuclear power, and various attendant environments such as those concerned with pre-launch handling and conditioning, and the launch itself.

Since a general study rather than one aimed at a selected mission was specified, the study has envisioned a second or third generation version of a communications satellite or military equivalent operating at some altitude between 150 km and 35,000 km at an unstipulated angle of inclination. However, it is recognized that such space-oriented tubes may also be used on vehicles going to the moon or other planets, particularly Mars. In consequence, a small part of the effort has been directed toward the needs of such missions. Intergalactic flights have been given little consideration.

1.2.2 Tube Materials

The materials studied have been classified into these categories: structural metals, magnetic metals, ceramics, glasses, and organic and inorganic dielectric materials used primarily for wire coatings and potting.

1.2.3 Microwave Tube

The investigation is generally restricted to amplifiers having the following ranges:

(1)	Frequency:	between approximately 1 Gc and 10 Gc.
(2)	Bandwidth:	as large as possible
(3)	Average power:	Adhering to the criterion $Pf^2 > 10$ where P is in kw and f is in Gc. (100w@X-band; 10 kw@L)

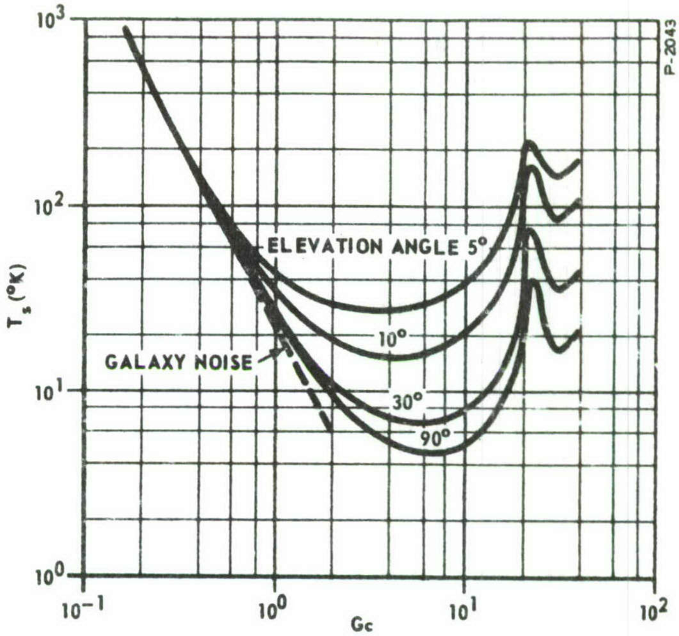


Figure 1-1 - Sky Temperature Seen by a Ground Antenna Versus Frequency for Various Antenna Elevation Angles(2)

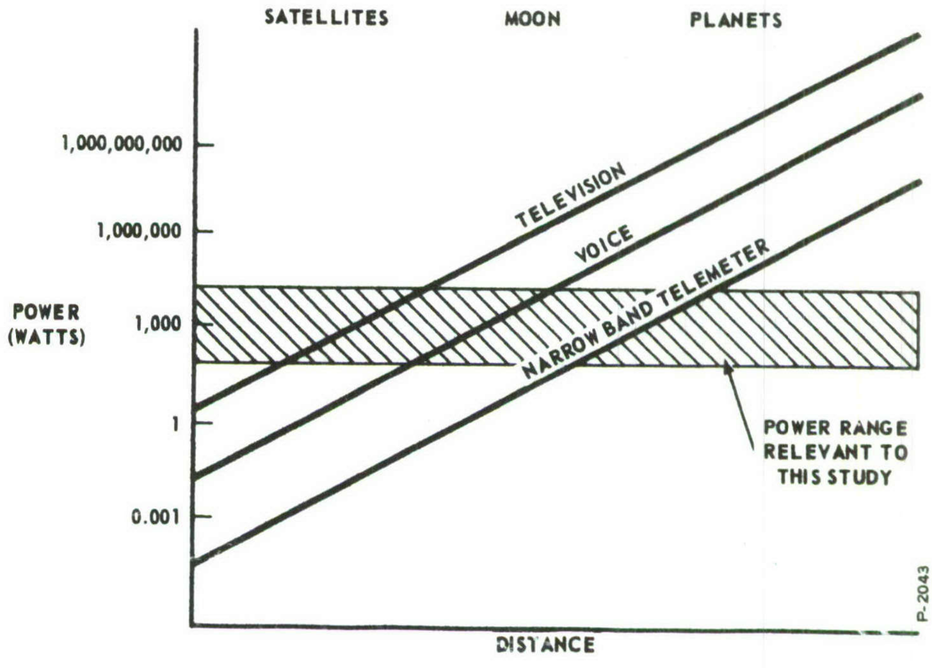


Figure 1-2 - Radio Power for Deep Space Probes(3)

The choice of frequency range is associated with the low noise temperature seen by a ground antenna aimed through the earth's atmosphere into space. This window in the spectrum is bounded by high galactic noise on the low end and atmospheric absorption on the high end, as shown in Figure 1-1.[2] Antenna sizes for this range are also reasonable. For space-to-space applications the higher frequencies can be exploited, leading to reduced antenna sizes without atmospheric attenuation problems.

The power criterion is chosen with an eye to probable power demands of next generation space missions, which are as yet unspecified. An approximate idea of the power requirements for various types of transmissions can be roughly ascertained from Figure 1-2;[3] here is plotted the satellite transmitter power necessary to send television, voice, and narrow-band telemetry signals to earth from various space distances. This graph assumes normal requirements rather than a perfect receiver, low noise amplifier, airborne antenna, and special storage techniques (i.e., slowing down the rate of sending).

The graph shows that the power range discussed in this report should be adequate for real-time TV transmission from orbiting satellites, or voice communications from the vicinity of the moon, and narrow band telemetry from interplanetary distances. If the ideal conditions could be more closely approached, for example, the first three of the above; then a real-time TV picture from Mars would require only about 10 kilowatts of power and with storage a single picture could be sent using only 10 watts.

1.3 ATTRIBUTES DESIRED IN A SPACE TUBE

Logic dictates that a space tube must be highly reliable, should operate efficiently, and should have minimum weight (mass). It must be capable of surviving through three distinct life phases: the earth phase prior to launch, the rise-to-orbit phase, and the orbital or space mission. In some cases there can, of course, be a re-entry and subsequent earth phase as well.

The stresses imposed on the tube package by these three environments are discussed and suitable tests to evaluate a tube are described.

1.4 APPROACH TO THE DESIGN OF A SPACE TUBE

First, the mission needs to be specified. Once this has been done the requirements on the tube can be roughly estimated from a graph such as Figure 1-2 or can be described more accurately in terms of the bits per second of information to be transmitted over the required distance. An illustrative graph of this type is shown in Figure 1-3.(2) This plot enables one to choose the power level needed to send the necessary bits per second from the satellite to the earth -- the earth antenna and space antenna sizes being parameters. A similar analysis can be applied in the case of a space-to-space link.

The choice of auxiliary power is now dictated by the electronic payload power requirements of which the tube power might well be a

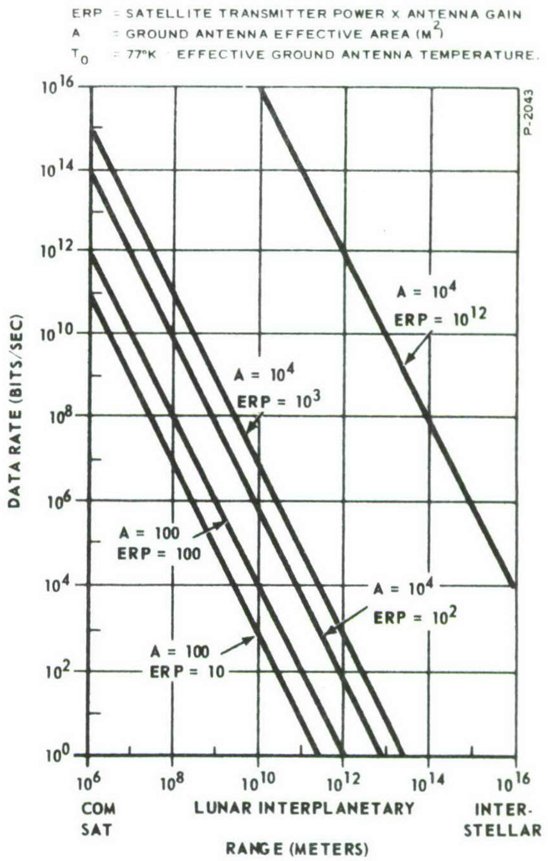


Figure 1-3 - Data Rate Versus Interplanetary Distance from an Earth Antenna to a Satellite for Various Effective Radiated Powers(2)

major requirement in an unmanned mission or but one of many power requirements in a manned mission. This power choice is very important for this reason: If the duration of the mission and the power demanded dictate the choice of a nuclear-reactor power source, then the radiation environment in which the tube must exist is substantially different from that presented by the natural environment of space. Figure 1-4 displays the regions of optimum coverage by various types of auxiliary power generators as they might well be for the next few years based upon the best knowledge available on the progress in various power source approaches.

Finally the design of the space tube is discussed. Here one has to consider the various tradeoffs involved in the quest for most satisfactory performance while adhering to the high reliability-high efficiency-low weight goals.

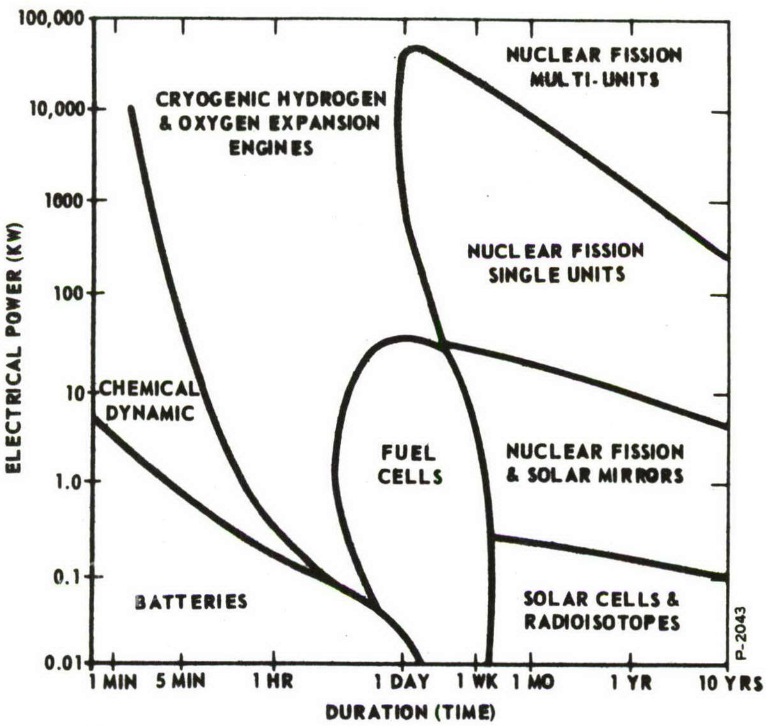


Figure 1-4 - Optimum Prime Auxiliary Power Application Areas - 1967-1970

The general limitations encountered are discussed in terms of the tube components; the gun, the focusing structure, the circuit, and the beam collector. Special problems facing the space tube designer are pointed out.

The importance of adequate and realistic testing of the space tube package is emphasized, and the theory and the practical implementation of such tests are described.

In conclusion, the lessons drawn from the entire study are summarized. Some new concepts are suggested and general guideline goals for the future are defined.

Before discussing the philosophy guiding the design of the space tube, it is informative to take a detailed look at the environment in which the tube must exist.

SECTION 2

NATURE OF ENVIRONMENT

This section details the three environments listed in subsection 1.2.1, viz., the natural space environment, the modified environment of the space vehicle interior which might include a nuclear power source, and the specialized environments of testing, storage, and sterilization. The natural space environment is described in terms of its composition (from sea level through the F region of the ionosphere), pressure, density, and temperature. Next, hazardous conditions such as micrometeoroids, electromagnetic radiation, ionizing radiation, and the magnetic field are described. In conclusion, the atmospheres of the moon and the planets Venus, Mars and Jupiter are discussed briefly. Available data on deep or interplanetary space are included.

2.1 NATURAL SPACE ENVIRONMENT

Space can be considered to begin about 160 km above the earth's surface or at the perigee of the lowest practical orbit for an earth satellite. Interplanetary space (that portion of space which is within the solar system but beyond the influence of individual planets) starts at several thousand kilometers above the earth and is interrupted comparatively briefly by the moon and its atmosphere and the other planets with their atmospheres. The volume beyond the solar system can be termed intergalactic space.

Some idea of the magnitude of the distance involved can be obtained from Table 2-1.

2.1.1 Atmospheric Pressure and Density

Anyone who has gone up in an express elevator or an unpressurized plane has been made aware that atmospheric pressure decreases with increase in altitude. But how low the lowest pressure in outer space may be has not yet been settled satisfactorily. Certainly it is a better vacuum than is attained with any but a very few laboratory vacuum systems, being beyond the range called ultra high vacuum. But whether the pressure is 10^{-12} or 10^{-20} Torr, or somewhere in between,

Table 2-1 - Selected Distances in Space

	Kilometers	Miles	Earth Radii
Altitude of Stratosphere	10 to 80	6 to 50	
Altitude of Ionospheric Region "D"	60 to 90	37 to 55	
Altitude of Ionospheric Region "E"	90 to 140	55 to 85	
Altitude of Ionospheric Region "F"	140 to 1300	85 to 800	
Altitude of Protonosphere	above 1300	above 800	
Mean Distance to the Moon	384,400	239,700	60.27
Mean Distance to the Sun	150,000,000	92,900,000	23,450
Perigee and Apogee of Mercury	165 & 250	102 & 160	
Perigee and Apogee of Telstar I	957 & 5633	600 & 3550	
Perigee and Apogee of Telstar II	971 & 10808	610 & 682	
Perigee and Apogee of Relay I	1312 & 7445	828 & 4700	0.21 & 1.19
Perigee and Apogee of Syncom I	34182 & 37014	21500 & 23300	5.44 & 5.95
Perigee and Apogee of Syncom II	35780 & 35793	22400	5.7
Perigee and Apogee of Imp. I	190 & 195,000	120 & 122,800	0.0306 & 31.2

P-2043

The distance to the planets Venus and Mars, at their point of closest approach, is more than 100 times the distance to the Moon.

is subject to question. It has not been measured directly and, in fact, calibration of gauges for pressures of 10^{-12} Torr and lower is still a controversial issue.*

Between 200 and 2500 km atmospheric pressure varies from day to nighttime and there is also a difference depending on the solar cycle (solar flare cycle, sunspot cycle). Figures 2-1, 2-2, 2-3, and 2-4 show these phenomena.

It can be seen in Figure 2-1[4,5,6] that at the altitudes traversed by the astronauts, the pressure outside their capsule is the high vacuum of good laboratory vacuum systems, 10^{-6} Torr. At an

*A Torr is 1/760 of a standard atmosphere and hence almost exactly equivalent to 1 millimeter of mercury. The unit was named after Evangelista Torricelli, the 17th century Italian mathematician and physicist.

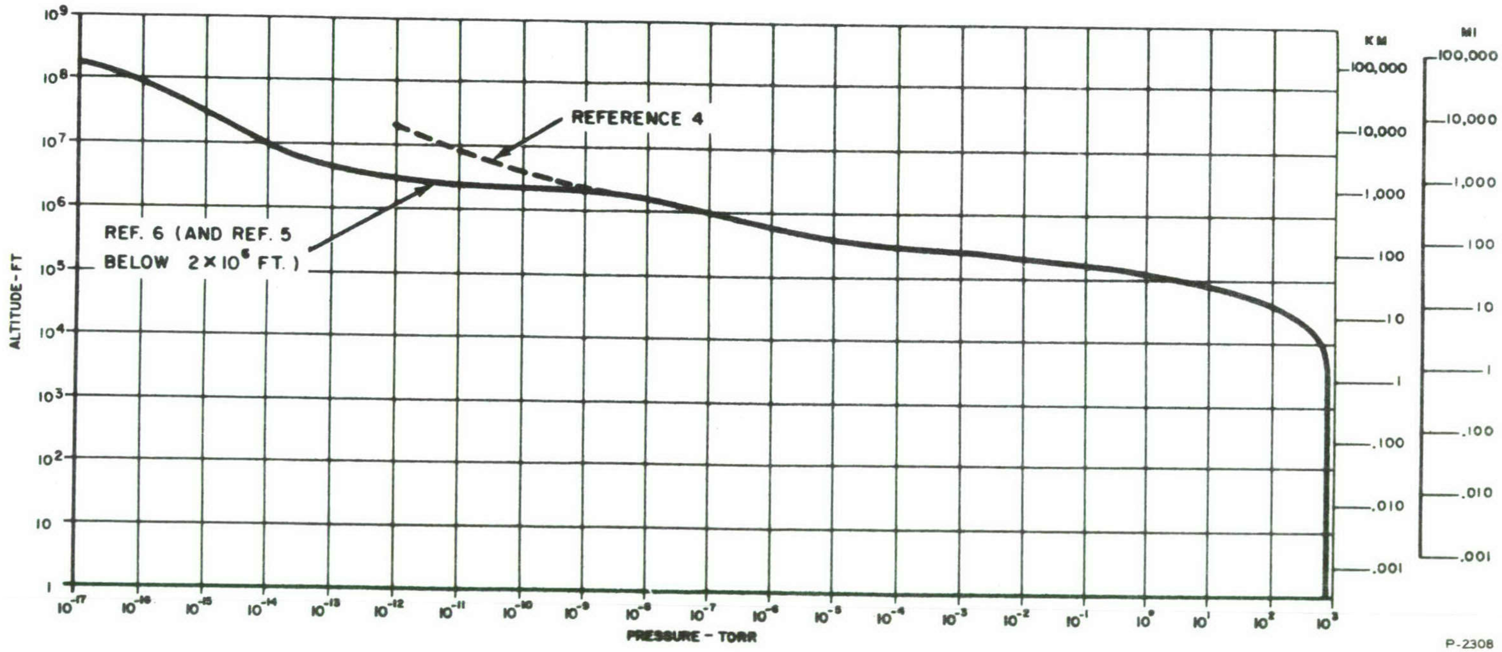


Figure 2-1 - Atmospheric Pressure[4,5,6]

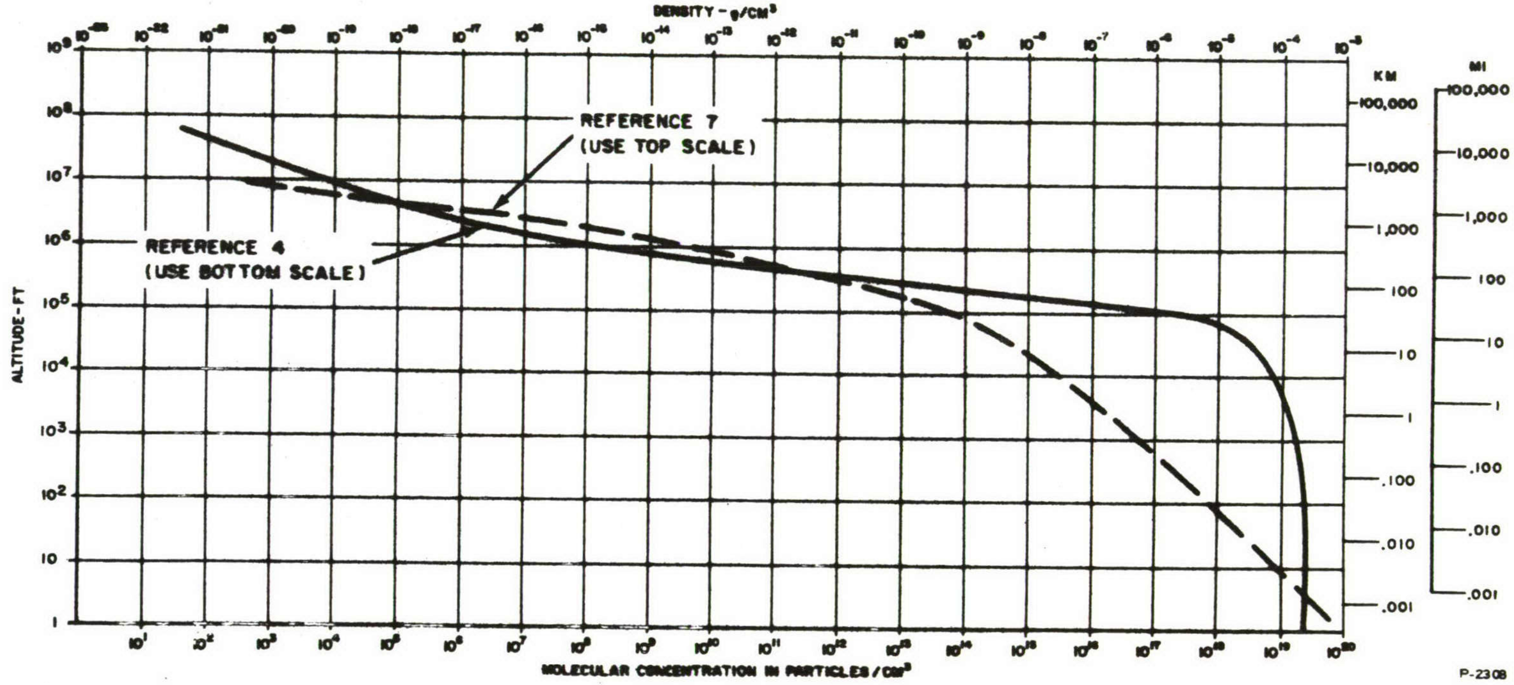


Figure 2-2 - Atmospheric Density in Grams/cm^3 and Particles/cm^3 (4,7)

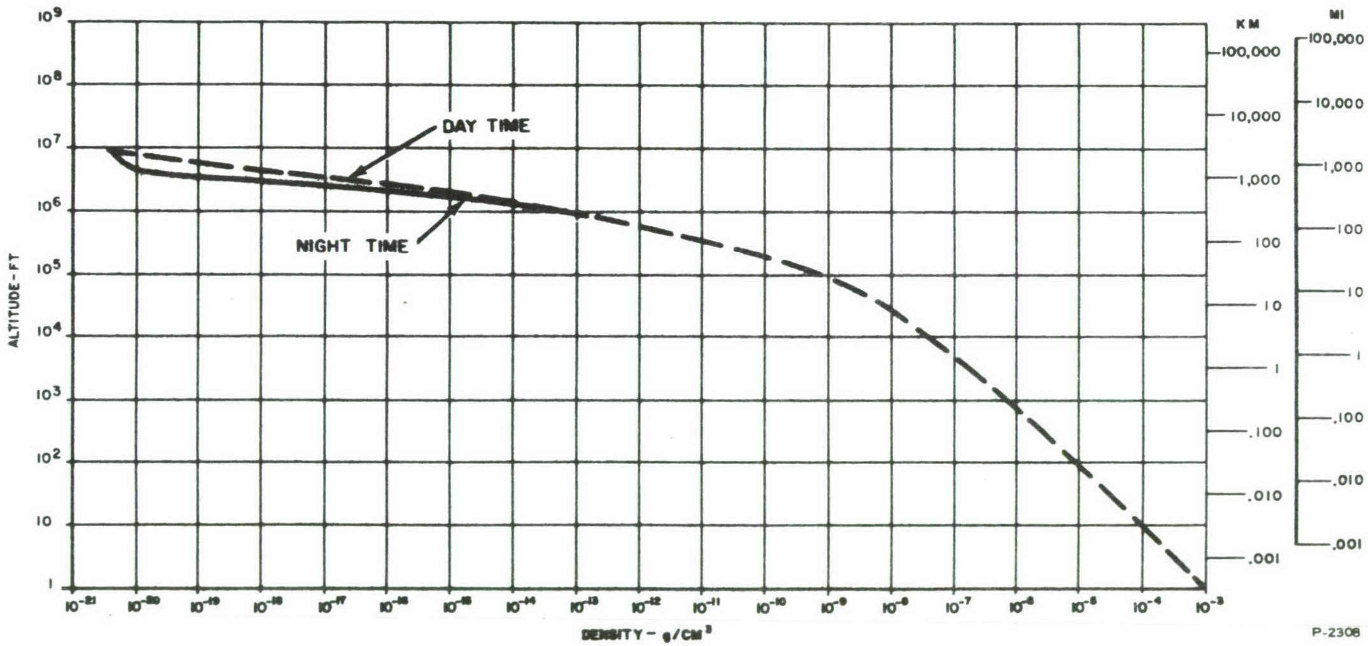


Figure 2-3 - Atmospheric Density Variations Between Daytime and Nighttime(7)

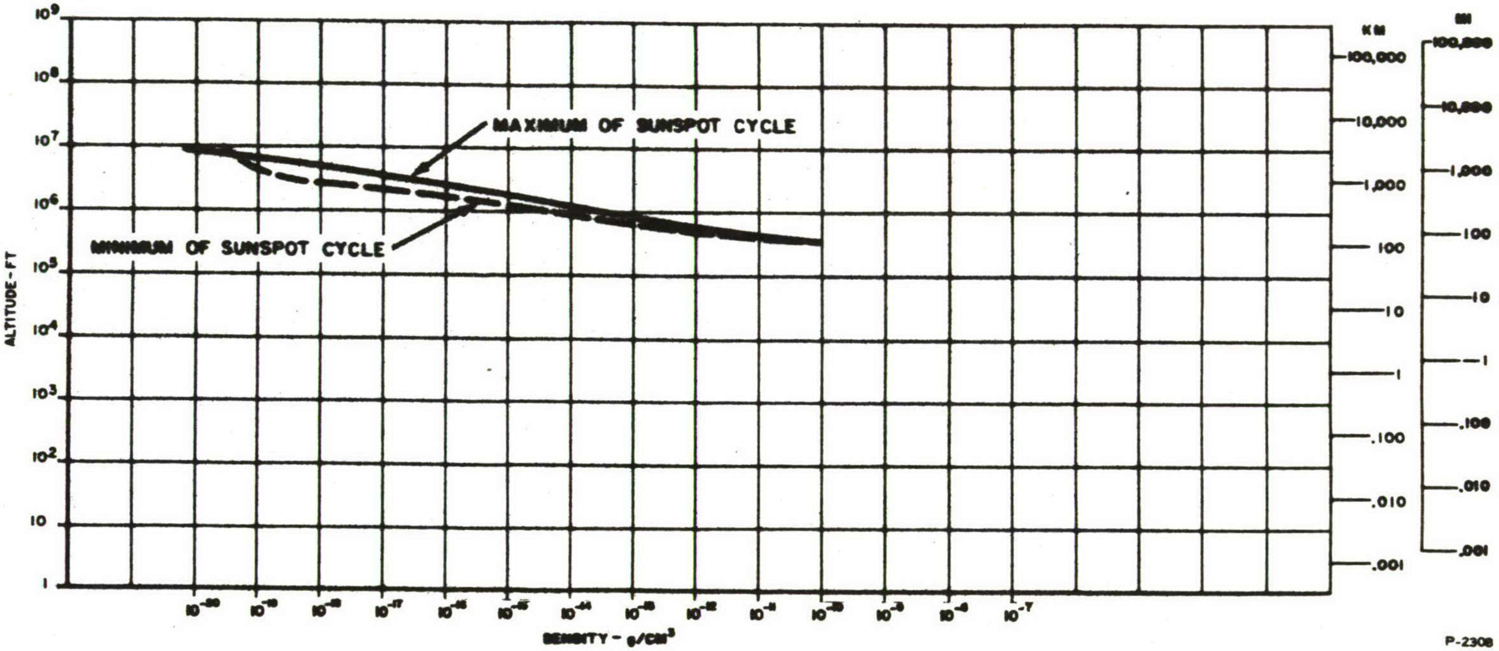


Figure 2-4 - Atmospheric Density Variations Due to the Solar Cycle(8)

800 km altitude this pressure is down to 10^{-9} Torr, a pressure achieved by only a few laboratory vacuum systems, which have special seals and bakeout facilities, cryopumping or liquid nitrogen baffling.

At such extremely low pressures, where the mean free path of gas molecules becomes so long, gas density is more meaningful than pressure. Figure 2-2[4,7] substitutes density for pressure in two unit systems, grams per cm^3 and particles per cm^3. For instance, at about 160 km altitude, the density is about 10^{-2} g/cm^3 and about 10^{11} particles/cm^3. At 2500 km the density has been reduced to 10^{-20} g/cm^3 and 10^5 particles/cm^3.

The daytime-nighttime difference is shown in Figure 2-3[7] and the solar cycle induced density variations are shown in Figure 2-4.[8] A short discussion of the solar cycle is found in subsection 2.1.6.3.

While these are the best figures now available for the pressure out in space, it should be emphasized that inside a space vehicle or satellite the pressure may be somewhat higher because of deliberate use of hermetic or labyrinth seals, partial sealing provided by structural members and pressure added by outgassing of components. This is discussed further in the chapter on material effects. It should also be added that direct experimental data for pressures and densities at large distance from the earth are meager at best.

2.1.2 Composition of the Earth's Atmosphere

A good example of inaccuracies appearing in reference works is found in the recent history of the knowledge of the composition of the earth's atmosphere at higher altitudes. This is because the need for information, temporarily at least, exceeded the available experimental facilities. In the last two years, two helium belts were found whose existence was apparently unsuspected at the time the Satellite Environment Handbook[8] and ASTM's Space Radiation Effects on Materials[7] were prepared by some of the best authorities in the field.

2.1.2.1 Sea Level

As the situation stands at this writing, there is no doubt about the nominal dry atmospheric composition at sea level as shown in Table 2-2.[7] The standard atmosphere tables apply below 20 km; there is a proposed standard up to 32 km and a speculative standard from 90 - 700 km.

It is in this region that recent discoveries of the Explorer satellites have altered previous estimates. Explorer VIII found a band of ionized helium starting at about 350 km and Explorer XVII[10] found a band of neutral helium with density ranging from 60 million atoms/cm^3 at 240 km to 1 million/cm^3 at about 900 km.

Above the helium belt, hydrogen ions or protons assume the most important role.

An interesting calculation of the composition of air at exospheric altitudes is provided by Singer.[11]* Instead of giving the composition with regard to altitude in kilometers, he uses the unit r/R, where r is the level or altitude he is discussing, and R is the level of the exospheric base (530 km). He assumes a temperature of 1500°K throughout the exosphere. Singer arrives at the figures shown in

Table 2-3 - Distribution of Major Exospheric Components with Altitude[11]*

r/R	Altitude (km)	Oxygen n/cm^3	Hydrogen n/cm^3	Ionized Oxygen (O+) n/cm^3	Ionized Hydrogen (H+) n/cm^3
1.000	530	4.0×10^7	10^4	9.0×10^5	
1.010	600	1.9×10^7		6.2×10^5	
1.025	700	6.4×10^6		3.6×10^5	
1.050	870	1.2×10^6		1.6×10^5	
1.075	1040	2.3×10^5		6.7×10^4	
1.100	1220	4.0×10^4	6.3×10^3	3.1×10^4	
1.125	1390	1.0×10^4		1.4×10^4	
1.150	1560	2.5×10^3		6.9×10^3	
1.175	1730	6.4×10^2		3.5×10^3	
1.200	1910	1.6×10^2	4.2×10^3	1.8×10^3	
1.250			3.5×10^3		
1.667			1.1×10^3		
2.000			5.7×10^2		10^3
2.500			2.7×10^2		5×10^2
3.333			1.1×10^2		2×10^2
5.000			3.5×10		70
10.000			6		10

P-2043

*The helium belts are not shown in this table, but data from Explorer satellites has proven their existence.

*Exosphere is defined as the region of the atmosphere from which molecules may escape out into space rather than being forced back by collisions with other molecules in the overlying atmospheres.

Table 2-3[11] where concentrations are given in particles/cm^3, by using exosphere theory, normalized to satellite-drag for oxygen, Lyman-alpha data for hydrogen, Alpert's electron density for ionized oxygen, and radio whistler data for ionized hydrogen. He notes that He, He^+, He^{2+}, O^{2+}, O^{3+} are not shown and predicts that they may be found to be important. At the time he gave the lecture which was afterwards expanded into the chapter of "Space Sciences," the neutral and ionized helium belts had not yet been found.

2.1.3 Atmospheric Temperatures

In order to understand the significance of the temperatures out in space, one must remember that what is called temperature represents the kinetic energy of the relatively few atoms in the vacuum of space. Hence the total amount of heat energy is negligible. Heat transfer is by radiation alone and not by convection or conduction. There is no natural convection below 10^{-3} Torr. A body in space is seldom in thermal equilibrium with its environment; the sun and other stars, the moon, and the earth radiate heat to the body, but the body in turn radiates heat to deep, dark space.

A calculation of the energy reaching a space capsule with no internal heat source from space and being reirradiated, gives an effective space capsule temperature of about 4°K (-454°F, 6° Rankine). Cold walls (behind which run liquid nitrogen) with temperatures of about -300°F are used[12] to duplicate these conditions in space chambers as closely as economically feasible. Figure 2-5[8,11,13] shows the kinetic temperatures[5] in space to be 1000 - 1500°K.

2.1.4 Meteoroid and Micrometeoroid Hazards

A meteoroid is a solid body made of stone or iron, weighing over 1 gram and moving around the sun in highly eccentric circles. There are so few meteoroids that the probability of a collision between a space vehicle and one of these bodies is negligible.

Micrometeoroids, which weigh under 1 gram by definition, may have created more of an impact on the imagination of semitechnical writers than on spacecraft. These clouds of tiny dust particles, most of them weighing less than a milligram, moving around in space at fantastic speeds (faster than can be duplicated in the laboratory) can be more easily visualized than some other properties. While they may be found

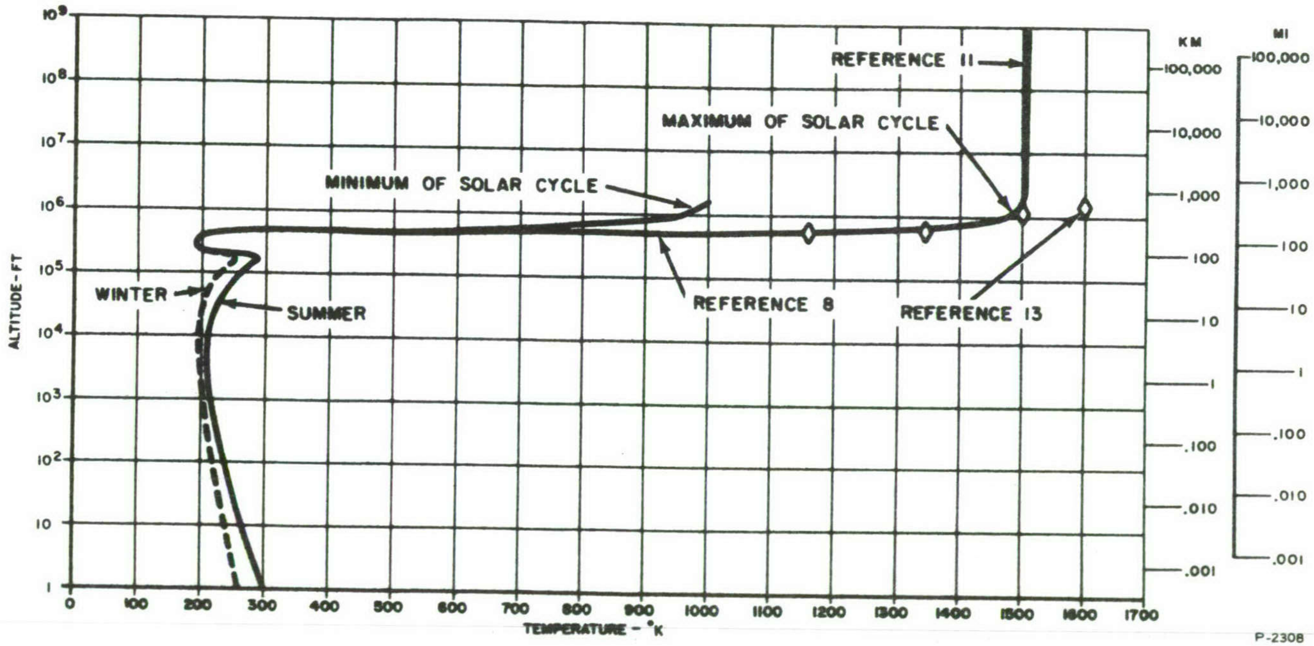


Figure 2-5 - Atmospheric Temperatures(8,11,13)

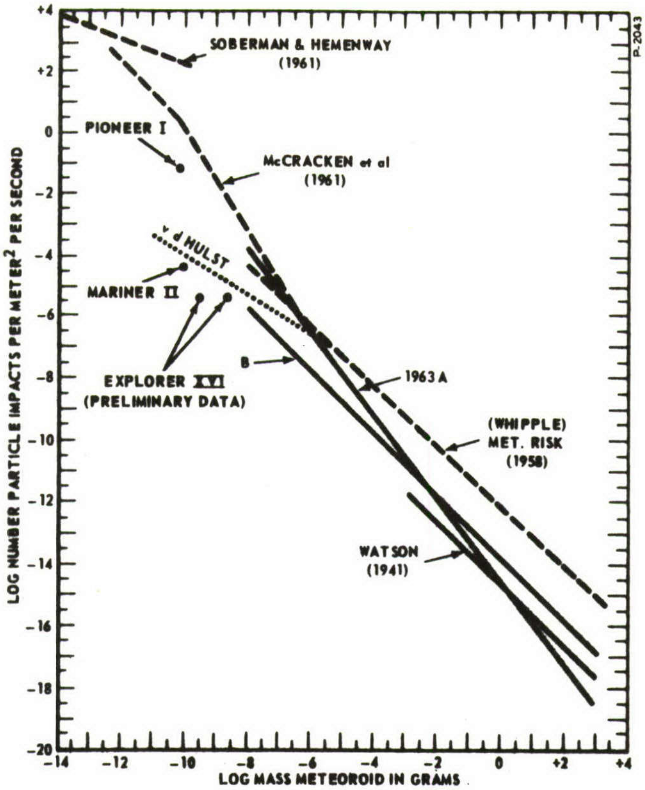


Figure 2-6 - Cumulative Meteoroid Impact Rates Near the Earth(14, 15)

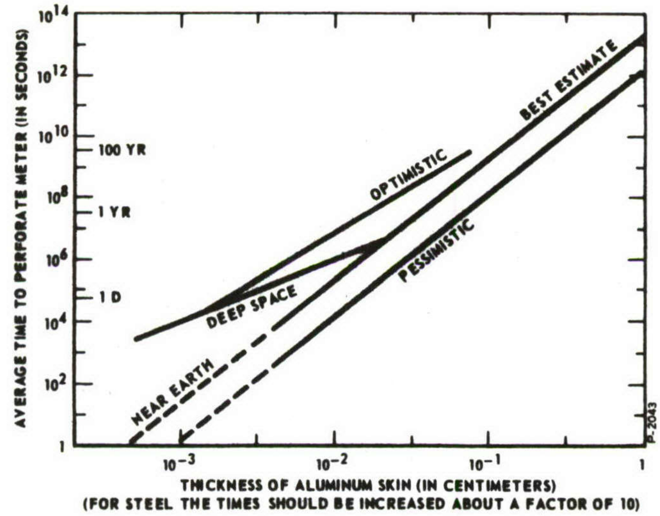


Figure 2-7 - Meteoroid Perforation of Thin Metal Skin in Space(14)

anywhere in space, because of their cometary and asteroidal origin, there appears to be a somewhat greater concentration along the earth's path around the sun than elsewhere.

Until recently only indirect micrometeoroid measurements were possible and as Whipple[14] points out, there have been changes in micrometeoroid data and refinements of the impact formulas. Using the best data available prior to that sent down by Explorer XVI, Whipple recalculated the cumulative meteoroid impacts near the earth. His "1963 A" curve (Figure 2-6)[14,15] has been generally accepted as the best estimate until the Explorer XVI data is analyzed. Preliminary reports on Explorer XVI seem to indicate that the micrometeoroid hazard is not quite as great as the 1963 A curve shows and that the most optimistic estimate on the amount of shielding needed (Figure 2-7)[14] is also correct.

Some idea of the flux of micrometeoroids can be obtained from the preliminary Explorer XVI data.[16,17] The microphones heard 15,000 impacts on an area of 3.56 square feet in 7-1/2 months, or 2.02×10^{-6} hits/meter^2/sec. This is more than 2 orders of magnitude lower than the 1963 A prediction. Only a few of these particles actually penetrated the skin of the gas sensors. These sensors could register only the first penetration of each cell, but there were enough untouched cells, so that statisticians can calculate penetration probabilities with a high degree of certainty, at least for satellites with the same orbit. There appears to be no evidence of serious variation of flux of particles with time. Tables 2-4[15,16,17] and 2-5[15] show the extent of micrometeorite penetration of the cells on Explorer XVI.

2.1.5 Electromagnetic Radiation

The total solar electromagnetic energy, also known as the solar constant, is defined as the rate at which energy is received from the sun upon a unit surface perpendicular to the sun's rays above the earth's atmosphere at its mean distance from the sun. It amounts to 2.0 gram-cal/cm^2/min, or, translated into other units, 2 pyrons or 140 milliwatts/cm^2.

Solar electromagnetic radiation can be divided into X-rays (1.0 to 200 Å), far ultraviolet (200 Å to 2000 Å), near ultraviolet

Table 2-4 - Micrometeorite Penetration on Explorer XVI[15,16,17]

Number of Cells	Thickness of Skin	Material	Total Area	No. of Cells Penetrated in 7-1/2 Months
100	1 Mil	Beryllium Copper	10.625 ft^2	44
40	2 Mil	Beryllium Copper	4.250	11
20	5 Mil	Beryllium Copper	2.125	0
32	1 Mil	Stainless Steel	1.56	6
24	3 Mil	Stainless Steel	2.07	
4	6 Mil	Stainless Steel	0.26	0
14	2 Mil	Copper Wire	0.68	1
32	3 Mil	Copper Wire	1.57	1

P-2043

Table 2-5 - Micrometeorite Penetration Rate[15]

Material	Thickness (mils)	cm x 10^{-3}	Penetration Rate (No./m^2/sec)
Beryllium copper	1	2.5	4.36×10^{-6}
Beryllium copper	2	5.1	2.62×10^{-6}
Stainless steel	1	2.5	2.23×10^{-6}

P-2308

(2000 Å to 3800 Å or 4000 Å*),[18] visible (from ultrviolet upper limit to 7000 Å or 0.7 micron), and infrared (0.7 micron to 7.0 microns).

Radiation of wavelength less than 2920 Å[18] does not reach the earth's surface, but is filtered out by the atmosphere near the earth. It has already been mentioned in subsection 2.1.2 that UV of 1223 Å wavelength affects the composition of the "D Region" of the ionosphere. It was also brought out that X-rays ionize the air in the "E Region" and that the helium II line at 340 Å affects the "F Region."

*Handbook of Chemistry & Physics, 43rd Edition, p. 2802, sets UV limit at 4000 Å. ASTMSTP 330, p. 15, uses 3800 A instead. Others have set the limit somewhat higher. This difference leads to substantial variations in percentage of solar energy in the UV range.

Table 2-6 - Solar-Spectral - Irradiance Data[8]

λ (μ)	H_λ (w/cm²μ)	P_λ (%)	λ (μ)	H_λ (w/cm²μ)	P_λ (%)	λ (μ)	H_λ (w/cm²μ)	P_λ (%)	λ (μ)	H_λ (w/cm²μ)	P_λ (%)
0.22	0.0030	0.02	0.395	0.120	8.54	0.57	0.187	33.2	1.9	0.01274	93.02
0.225	0.0042	0.03	0.40	0.154	9.03	0.575	0.187	33.9	2.0	0.01079	93.87
0.23	0.0052	0.05	0.405	0.188	9.65	0.58	0.187	34.5	2.1	0.00917	94.58
0.235	0.0054	0.07	0.41	0.194	10.3	0.585	0.185	35.2	2.2	0.00785	95.20
0.24	0.0058	0.09	0.415	0.192	11.0	0.59	0.184	35.9	2.3	0.00676	95.71
0.245	0.0064	0.11	0.42	0.192	11.7	0.595	0.183	36.5	2.4	0.00585	96.18
0.25	0.0064	0.13	0.425	0.189	12.4	0.60	0.181	37.2	2.5	0.00509	96.57
0.255	0.010	0.16	0.43	0.178	13.0	0.61	0.177	38.4	2.6	0.00445	96.90
0.26	0.013	0.20	0.435	0.182	13.7	0.62	0.174	39.7	2.7	0.00390	97.21
0.265	0.020	0.27	0.44	0.203	14.4	0.63	0.170	40.9	2.8	0.00343	97.47
0.27	0.025	0.34	0.445	0.215	15.1	0.64	0.166	42.1	2.9	0.00303	97.72
0.275	0.022	0.43	0.45	0.220	15.9	0.65	0.162	43.3	3.0	0.00268	97.90
0.28	0.024	0.51	0.455	0.219	16.7	0.66	0.159	44.5	3.1	0.00230	98.08
0.285	0.034	0.62	0.46	0.216	17.5	0.67	0.155	45.6	3.2	0.00214	98.24
0.29	0.052	0.77	0.465	0.215	18.2	0.68	0.151	46.7	3.3	0.00191	98.39
0.295	0.063	0.98	0.47	0.217	19.0	0.69	0.148	47.8	3.4	0.00171	98.52
0.30	0.061	1.23	0.475	0.220	19.8	0.70	0.144	48.8	3.5	0.00153	98.63
0.305	0.067	1.43	0.48	0.216	20.6	0.71	0.141	49.8	3.6	0.00139	98.74
0.31	0.076	1.69	0.485	0.203	21.3	0.72	0.137	50.8	3.7	0.00125	98.83
0.315	0.082	1.97	0.49	0.199	22.0	0.73	0.134	51.8	3.8	0.00114	98.91
0.32	0.085	2.26	0.495	0.204	22.8	0.74	0.130	52.7	3.9	0.00103	98.99
0.325	0.102	2.60	0.50	0.198	23.5	0.75	0.127	53.7	4.0	0.00095	99.05
0.33	0.115	3.02	0.505	0.197	24.2	0.80	0.1127	57.9	4.1	0.00087	99.13
0.335	0.111	3.40	0.51	0.196	24.9	0.85	0.1003	61.7	4.2	0.00080	99.18
0.34	0.111	3.80	0.515	0.189	25.6	0.90	0.895	65.1	4.3	0.00073	99.23
0.345	0.117	4.21	0.52	0.187	26.3	0.95	0.0803	68.1	4.4	0.00067	99.29
0.35	0.118	4.63	0.525	0.192	26.9	1.0	0.0725	70.9	4.5	0.00061	99.33
0.355	0.116	5.04	0.53	0.195	27.6	1.1	0.0606	75.7	4.6	0.00056	99.38
0.36	0.116	5.47	0.535	0.197	28.3	1.2	0.0501	79.6	4.7	0.00051	99.41
0.365	0.129	5.89	0.54	0.198	29.0	1.3	0.0406	82.9	4.8	0.00048	99.45
0.37	0.133	6.36	0.545	0.198	29.8	1.4	0.0328	85.5	4.9	0.00044	99.48
0.375	0.132	6.84	0.55	0.195	30.5	1.5	0.0267	87.6	5.0	0.00042	99.51
0.38	0.123	7.29	0.555	0.192	31.2	1.6	0.0220	89.4	6.0	0.00021	99.74
0.385	0.115	7.72	0.56	0.190	31.8	1.7	0.0182	90.83	7.0	0.00012	99.86
0.39	0.112	8.13	0.565	0.189	32.5	1.8	0.0152	92.03			

P-2043

λ is wavelength; H_λ is spectral irradiance; and P_λ is the percentage of the solar constant associated with wavelengths shorter than λ.

Table 2-6[8] gives the spectrum of the solar radiation above the earth's atmosphere. Wavelength is given in microns (a micron is one millionth of a meter or 10,000 Angstrom units). It can be seen that about 40 percent of the solar electromagnetic energy is in the visible range; about 50 percent in the infrared.

From the viewpoint of possible damage to materials used in space vehicles operating within 30,000 miles of earth, electromagnetic radiation from sources other than our own sun appears to be negligible.

2.1.6 Space Radiation

In this section only a simple summary of the Van Allen and Starfish Belts will be given and the ionizing radiation associated with solar flares will be discussed briefly. A more theoretical approach to the study of the Van Allen and Starfish Belts is found in Appendix A.

2.1.6.1 Van Allen Belts

The discovery of the Van Allen Belt was one of the more significant achievements of the International Geophysical Year. It consists of a vast belt of magnetically trapped electrons and protons surrounding the earth, centered above the earth's geomagnetic equator. Because this radiation is a belt, and not a spherical envelope, satellites in the so-called polar orbit are not seriously affected by it.

The Van Allen Belt extends from an altitude of about 375 km above the earth to a height about 1/5 of the way to the moon. The outer limit is so affected by solar winds and other phenomena that it can be anywhere from about 65,000 km to 90,000 km altitude. Formerly this belt was thought to be two separate belts, but more recent figures indicate that the separation is not as clear as originally thought. The inner portion of the belt consists mainly of protons and the outer portion consists mainly of electrons. Quantitative flux data are found in the appendix.

These protons and electrons interact with some materials to do serious damage to the material properties. They act in a manner analogous to the gamma part of radiation from a nuclear reactor, i.e., by action on the orbital electrons of the atom, causing ionization. (Protons can also cause displacements from the crystal lattice, but the extent of this type of action in the Van Allen Belt need

not cause alarm except for solar cells and possibly transistors.) For this reason, when testing material in a laboratory to find out how it will react to ionizing radiation in the Van Allen Belt, the best simulation would be found in the use of a gamma source in a vacuum with chamber walls at a cryogenic temperature, an obviously expensive method. Naturally, if the space vehicle orbiting in the Van Allen Belt is powered with a nuclear power source, for instance SNAP-8, then the vehicle's environment is modified from the natural environment and simulated test conditions must be altered to match. Radiation eminating from the reactor would be the dominant damaging source and the space radiation could be forgotten.

Estimates on the amount of radiation in the Van Allen Belt have been subject to change as the hundreds of millions of bits of information from each new rocket and satellite are reduced to significant equations and curves.[19]

The data in Appendix A is based on findings published up to about August 1963, and concludes that in the worst case (equatorial orbit at 10 to 20 x 10^3 km altitude) the exposure rate on the surface of a spacecraft would be 9 x 10^5 rads/hour. Inside the vehicle the dose will be reduced considerably. With shielding equivalent to 1 gm/cm^2 aluminum (a thickness of 0.37 inch), the worst will be 80 rads/hour at 2 to 9 x 10^3 km altitude. The published literature on this subject shows such a divergence of opinion and so little detail on the calculations and assumptions leading to the exposure dose quoted that it was felt necessary to do the calculations ourselves. Appendix A shows the calculations and the basis for them.

2.1.6.2 Starfish Belt

Starfish, the artificial radiation belt brought into being by the Starfish high altitude nuclear test over Johnson Island in July 1962, is slowly disappearing. At its worst, it resembled the Van Allen Belt in intensity except that it consists solely of electrons. Figure 2-8[20] shows the intensities as measured by Explorer XV.

Starfish has been blamed for the failure of Telstar I (transistor failure), Traac and Ariel (damaged solar cells).[21] The transitor failure was probably due to surface damage caused by ionization; the solar cells appear to have suffered bulk damage.

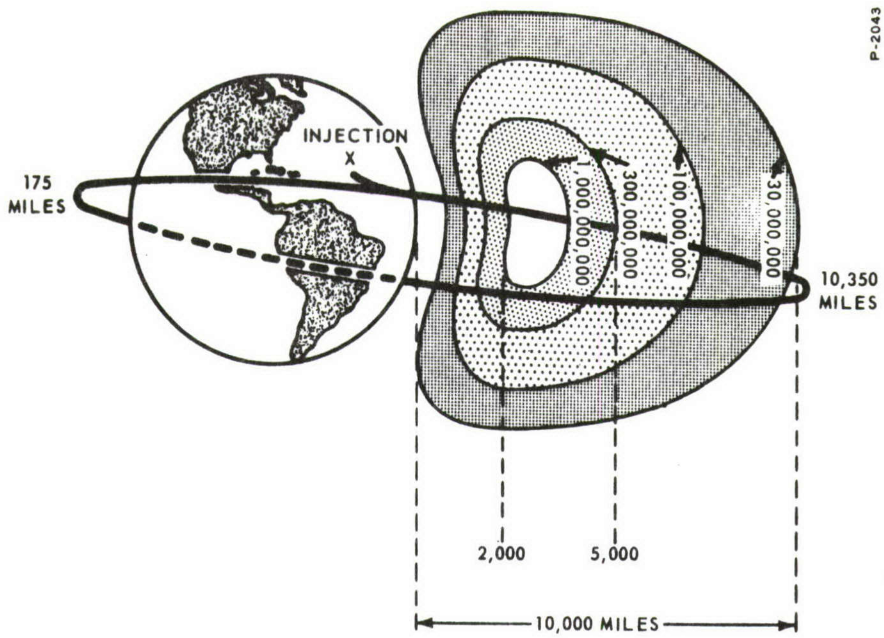


Figure 2-8 - Explorer XV Orbit Through the Starfish Artificial Radiation, July 9, 1962[20]

At the rate this artificial radiation belt is disappearing it may last another 30 years. Electrons having altitudes below 500 km are decaying in periods of weeks to months. There has been some decrease at an altitude of 3 earth radii.[22] However, Wilmot Hess[23] of Goddard Space Flight Center has suggested informally that it is possible that the events of the next solar cycle may speed up the process and that the Starfish artificial belt will no longer be a hazard ten years from now.

2.1.6.3 Solar Flare

Workers from various fields have given this phenomena many names. From the view point of possible damage to the electron tube, "solar proton event" may be the most descriptive; "polar cap absorption event" (PCA) describes one aspect of the phenomena; "solar cosmic-ray event" is another name for the same thing.

Figure 2-9[24] shows the development of a typical solar flare. A relative time scale is shown because of the wide disparity between events. The flare starts out near a previously observed sun

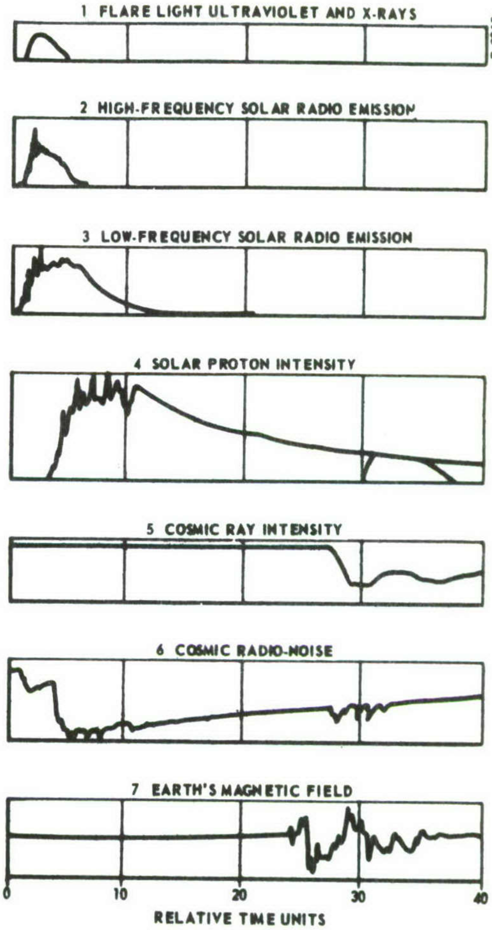


Figure 2-9 - Development of a Solar Flare(24)

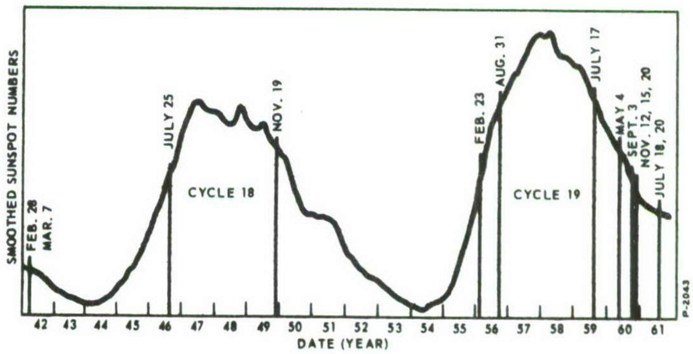


Figure 2-10 - Distribution of Cosmic Ray Events Detected at Sea Level as a Function of the Solar Cycle(26)

spot; there is a sudden flare of light accompanied by solar radio emission. The lower frequency radio emission lasts some hours longer than the high frequency. As the visible flare is dying down the solar proton intensity starts to increase, reaching a high some hours after the beginning of the phenomena. Some particles may persist for periods of 10 to 12 days.

These protons are high energy particles whose flux density may be as high as 10^6/cm^2-sec for protons of 20 mev to 500 mev, although 10^4/cm^2-sec is more typical even of large flares. There may be an accompanying electron flux of 10^6 or 10^7 electrons/cm^2-sec (50 Kev). This should be compared with Van Allen Belt flux densities shown in Appendix A. It can be seen that 10^7 electrons/cm^2-sec is 2 orders of magnitude worse than the highest part of the high energy proton curve in Figure A-1. However, the short duration of the solar proton event means that the total dosage will be about 10^5 rads or less.[25] This is especially important in the case of manned vehicles and of significance in the selection of organic dielectrics and semi-conductor components.

The solar cycle has an 11-year activity cycle as shown in Figure 2-10.[26] There appears to be a tendency for flares with large high-energy-particle flux to occur during a period of increase or decrease of sun spot activity rather than at the maximum. Malitson and Webber[27] in their listing of major events during the period 1956 - 1961 show that class 3 and 3+ events occurred on the dates shown in Table 2-7.*[27]

2.1.6.3.1 <u>Apollo Space Radiation Warning System</u> - Travel during times of solar flare activity can be avoided by recognizing three warning phenomena.[28]

(1) Large solar proton events tend to occur in groups of two or more, spaced a day or so apart. Allowing two days for radiation to decrease, this would mean that missions would not be launched the week after first sighting a solar flare.

---

*The importance of a flare increases with class number from Class 1- to 3+. The latter has an area approaching 5/1000 of the visible solar hemisphere.

Table 2-7 - Major Proton Events[27]

Date	Class 3	Class 3+
February 23, 1956		x
August 31, 1956	x	
January 20, 1957		x
July 3, 1957		x
August 29-31, 1957 (Uncertain)		
October 20, 1957		x
March 23, 1958		x
July 7, 1958		x
August 16, 1958		x
August 22, 1958	x	
August 26, 1958	x	
May 10, 1959		x
July 10, 1959		x
July 14, 1959		x
July 16, 1959		x
April 1, 1960	x	
April 28, 1960	x	
May 6, 1960 (Uncertain)		
September 3, 1960	x	
November 12, 1960		x
November 15, 1960		x
November 20, 1960	x	
July 11, 1961	x	
July 12, 1961		x
July 18, 1961		x
July 20, 1961		x
September 28, 1961	x	

P-2043

(2) Hydrogen alpha enhancement is the first sign of a flare.

(3) Microwave activity increase occurs very shortly thereafter with proton flux becoming noticeable not less than an hour later and building up to a maximum in an appreciable length of time. (This is also shown in Figure 2-9.)

The Apollo Space Radiation Warning System will predict these proton events by advance monitoring. This warning system is based on solar telescopes with H filters and microwave detection systems with manual and automatic readouts as well as systems for sending data from a number of stations in various parts of the world to the Manned Space Vehicle Center near Houston.

In the several years before Apollo is launched, it is hoped that analysis of data in proton events will make possible more than an hour's notice for future events. This monitoring will use the three clear channels (at 1400 - 1427 megacycles, 2690 - 2700 megacycles, and 4990 - 5000 megacycles) being established by international arrangements.

With an hour's warning, it is possible to shield astronauts on manned vehicles, and remote control equipment on unmanned vehicles, by making some physical rearrangement on board the vehicle to protect the most sensitive components. For instance, shutters or louvers could be lowered to shield an electronic "black box." Some protection can be afforded by turning off power in those cases where transistors are more radiation sensitive in biased condition than unbiased. This may mean that such components will be inoperable until original arrangements are restored.

2.1.6.3.2 Radiation Damage on Interplanetary Missions and Deep Space Probes - High thrust launch vehicles,[29] can go through the Van Allen Belt so fast that Van Allen and Starfish Belt radiation is of minor consequence compared to the damage done by a class 3 or 3+ solar flare.

A low thrust vehicle launched along an equatorial trajectory will need some shielding because of the high total dosage from the long stay in the Van Allen Belts and will thus be adequately protected against solar flare and galactic radiation.

2.1.6.4 New Radiation Zone

Very recent news items[30,31] report that sensors aboard the Interplanetary Monitoring Probe (IMP), launched into orbit between 120 and 122,800 miles from Cape Kennedy on November 26, 1963, have detected an extensive region of high energy radiation beyond the previously known reaches of the earth's radiation belts. The hitherto unknown energy zone appears to fan out beyond the Van Allen Belts on either side of the earth and to trail aft in a kind of "wake" in the direction away from the sun. Indications are that the flux in this new zone of radiation is probably too low to cause serious concern to space travelers.

2.1.6.5 Sputtering

Sputtering consists of bombarding surfaces with high energy ionized gases, with the result that the ions knock atoms out of the surface and into space. This technique is used on earth to coat a second surface and is frequently confused with true vacuum evaporation techniques.

McKeown,[32] reporting on research carried out at General Dynamics/Astronautics under auspices of Office of Naval Research and USAF, Cambridge Research Laboratories and USAF Space Systems Division, reported that the erosion due to sputtering on a gold surface in the upper atmosphere amounts to between 40 and 110 Å/year. This is based on measurements on Discoverers XXVI and XXXII. Gold was chosen because it has one of the highest sputtering rates of any element. One Angstrom unit is 3.9×10^{-9} inch or 0.004 microinch. These figures would seem to indicate that one would not expect any appreciable surface roughening as a result of sputtering.

2.1.7 Magnetic Field

Johnson and Webb,[33] in discussing Mariner II results state that the interplanetary magnetic field is much more irregular than was generally anticipated. The average field in the vicinity of the earth's orbit was observed to be about 5γ (1γ equals 10^{-5} gauss).

A highly detailed description of field intensity and magnetic shell parameter around the earth itself, based on computer calculations, was prepared by General Electric's Technical Military Planning Operation.[34] It shows, for instance, that at sea level the constant

magnetic field intensity in the region of the South Atlantic Anomaly is as low as 0.24 at the center; at 800 km the intensity is down to 0.18; at 2000 km there is a large area inside the 0.15 line. Figure A-4 gives additional data.

2.1.8 Lunar and Other Planetary Atmospheres

2.1.8.1 The Moon

The atmospheric pressure has been estimated as being about 3 orders of magnitude greater than that of outer space[35] and may consist principally of hydrogen[36] which reached the moon as a stream of protons from the sun and was trapped in the lunar surface lattice. A number of authors have postulated that the landing of a vehicle on the moon might raise a cloud of dust which could interfere with the operation of sensitive instrumentation and electronic gear. The lunar surface temperature at the lunar equator varies from 389°K to 122°K.[37]

2.1.8.2 Venus

Mariner II resolved some of the questions regarding the atmosphere surrounding Venus. The surface temperature is not only hot, 700°K, but dry and hostile to terrestrial life.[38] Venus is covered by cold dense clouds, the atmosphere above which contains little if any carbon dioxide although the clouds are known to have a substantial CO_2 concentration.[39] Mariner II also determined that Venus does not have the high density electron ionosphere some scientists have suggested.

2.1.8.3 Mars

The probable composition of the Martian atmosphere according to Rasool[40] is shown in Table 2-8. (M-atm is the thickness of a homogenous atmosphere in meters at 0°C and 760 mm.) The approximate temperature at the surface may vary from 200°K to 300°K, go down somewhat and up again as the altitude increases as shown in Figure 2-11.[41]

2.1.8.4 Jupiter

The atmosphere of Jupiter is still subject to question. Methane and ammonia have been detected spectroscopically; hydrogen has recently been found and it seems reasonable to believe

Table 2-8 - Possible Martian Atmosphere[40]

Gas	Amount, M-atm	% Volume
Nitrogen	About 1675	95.0
Argon	About 50	2.5
Carbon Dioxide	About 35	2.0
Oxygen	<2.4	<0.15
Water	$<2 \times 10^{-3}$ g/cm^2	

P-2043

Table 2-9 - Possible Composition of Jovian Atmosphere[40]

Gas	%
Helium	97.2
Hydrogen	2.3
Neon	0.39
Methane	0.063
Argon	0.064
Ammonia	0.0029

P-2043

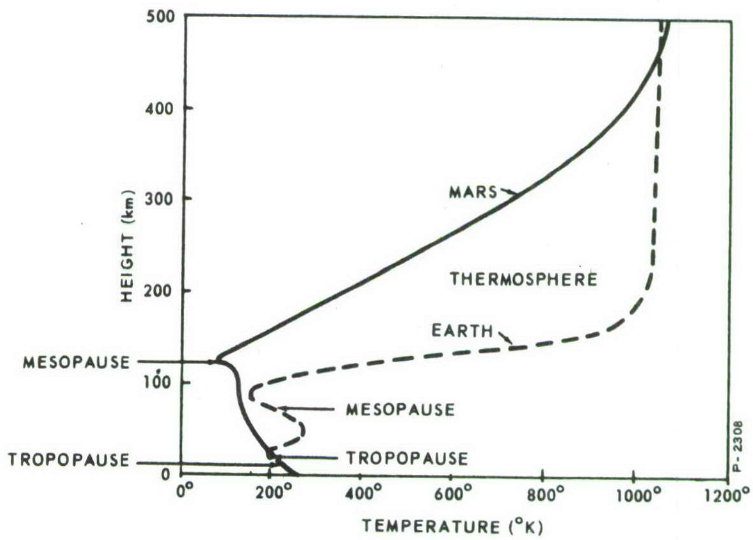


Figure 2-11 - Mars Model Atmosphere[41]

that helium exists in substantial amounts. Öpik, as quoted by Rasool,[40] proposes the composition shown in Table 2-9. The temperature is probably very low and there may be Van Allen type belts around Jupiter.

2.2 MODIFICATION OF SPACE ENVIRONMENT BY THE VEHICLE

2.2.1 Temperature and Pressure

In almost all satellites and space vehicles, if not all of them, there is some region on the inside which never reaches thermal temperature equilibrium with the outside. Thermal control coatings on the outside, heat producing instrumentation and power sources inside, gas jets to correct the direction the vehicle is moving, special heaters and coolers all modify the environment seen by the various components. These heaters and coolers are used to keep electronic gear and instrumentation, etc., within their operating temperature ranges. In manned vehicles, of course, the astronaut must also be provided with a temperature ambient in which he can operate efficiently.

In calculating temperatures at various parts of the vehicle, the presence of a large store of liquified gases will be found to have a very significant cooling effect.

Since heat dissipation in a vacuum is by radiation only and not conduction or convection, one would expect more local "hot spots" in orbiting space vehicles than on earth. This situation is one of the factors which has led to "thermal-vacuum" test requirements for electronic "black boxes."

The pressure, too, may vary widely from the outside pressure. Conservative design calls for much hermetic sealing of moving parts, electronic packages and, of course, the astronaut. Studies of labyrinth seals show that it is frequently possible to design bearings, for instance, where the balls may never see a pressure below 10^{-4} Torr. In many cases partial seals have been provided unintentionally by other requirements. In other cases, outgassing from some part has raised the pressure in its vicinity.

2.2.2 Micrometeoroids and Electromagnetic Radiation

While the outside of the vehicle will be exposed to the hazards of micrometeoroids and short ultraviolet rays, both hazards

are readily shielded so that they provide no problem to somewhat sheltered components. Explorer XVI indicated that only a few mils material thickness protects against the dust particles of space. It is well known that of the commonly used tube materials, quartz is the principal one which is transparent to UV.

2.2.3 Nuclear Power Source

As has been mentioned in the introduction, the problem of providing adequate power to run all the equipment and instruments which one would like to put on satellites and space vehicles has led to a number of studies on the possibility of using nuclear power. At present nuclear power is the only source known to be feasible where more than 10 kw is required. SNAP-8 is one of the proposed power packages on which a good deal of preliminary design work has been done. It is scheduled to fly prior to 1970 and appears to be the best power source where there is a long term need for high power; as in direct television and other communication equipment on an exploring vehicle. The advantages of nuclear power over solar cells increase as one travels farther from the sun, because the decrease in solar constant reduces the power output of solar cells.

The SNAP-8 system is now estimated to weigh over 3500 pounds or slightly over 100 pounds/kilowatt electrical.[42] The shielding specifications have been increased substantially over earlier figures, which provided a total exposure of 10^{13} nvt and 10^{6} rads (one year mission). This new specification (10^{12} nvt and 10^{6} rads) qualifies a number of electronic components, especially diodes and transistors, which were formerly banned from nuclear powered vehicles solely because of inadequate radiation resistance. Whether the continuing developments in the way of more radiation-resistant wire insulation, transistors, electron tubes, lubricants, etc., will bring about another change in specifications within the next two years is unpredictable. However, considerable concern is being expressed over the additional shielding weight; and trade off studies of later versions of nuclear powered space vehicles are very likely to show advantages of radiation hardening of circuitry over the heavier shielding, leading to changes in specifications.

Because of this and because it may be necessary to place a traveling wave tube with serious heat dissipation problems some distance from the rest of the electronic packages, the figures of 10^{12}

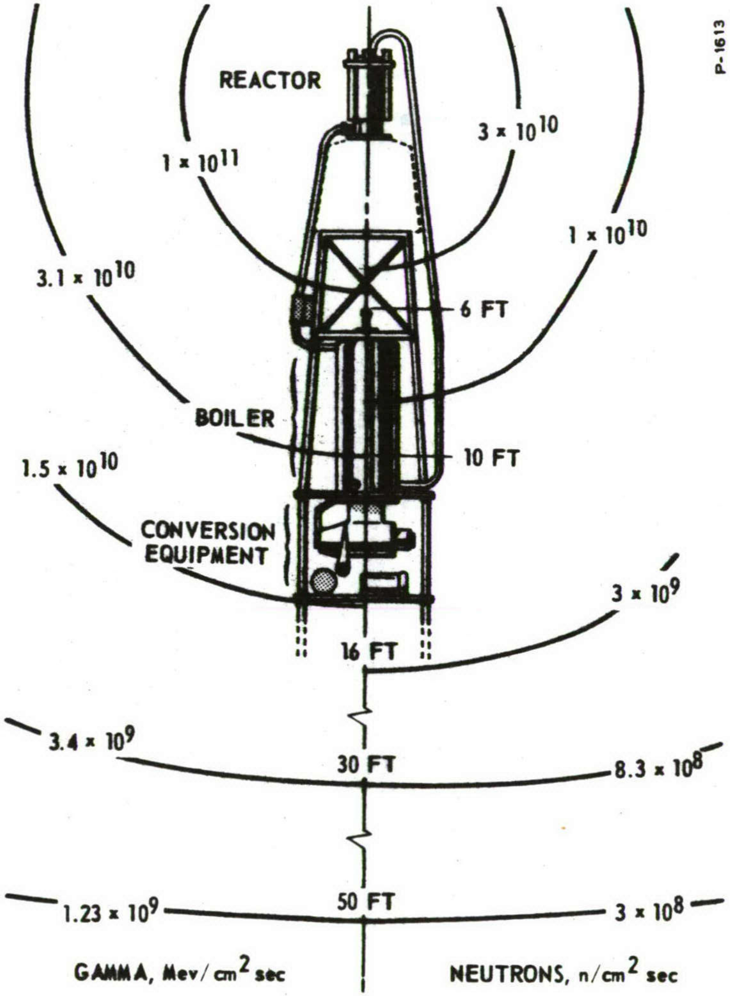


Figure 2-12 - Radiation Environment of Typical 300 kwth Nuclear Power Source (Unshielded)(43)

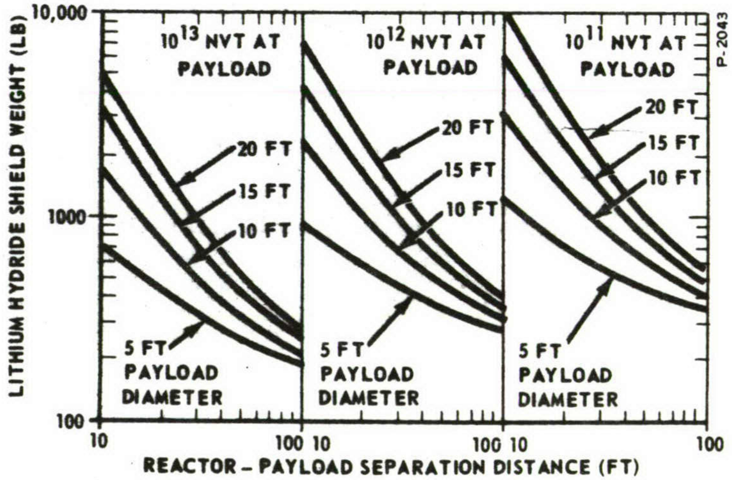


Figure 2-13 - Weight of Lithium Hydride Required for Shadow Shields for Various Shield Criteria(44)

nvt (fast neutrons) and 10^6 rads (gamma radiation) are being taken as minimum, rather than maximum, values of radiation from a nuclear power source.

Figure 2-12[43] shows how radiation levels fall off with distance in unshielded environments.

Figure A-7 shows the effect which 1 g/cm^2 aluminum shielding has on space radiation. Similar calculations are made for the effect of shields in reactors. Because of the interest in the SNAPs comparisons have also been made on shielding capability versus weight and volume for many materials other than aluminum. Figure 2-13[44] shows shielding calculations using lithium hydride shields. When heavy shielding is considered for nuclear powered vehicles, good design practice calls for taking advantage of its structural properties like tensile strength, compressive strength, hardness, etc.

2.3 ADDITIONAL ENVIRONMENTS

Several environments, which are neither the space environment nor the modification discussed in the previous section, enter into the materials feasibility study. They are:

(1) Earth-bound test conditions

(2) Storage and transportation prior to launch

(3) Sterilization requirements

(4) Launch conditions

2.3.1 Earth-Bound Test Conditions

Environmental tests are limited by an interesting restriction; that the material or component remain in a condition where its change in properties can be determined either during or after exposure to the simulated alien environment. This places some harsh restriction on nuclear radiation testing. If the material or component is "hot" for some time after the irradiation and must be handled by remote control, obviously, it becomes difficult and costly, or even sometimes impossible, to perform the desired post-irradiation tests.

The need for extreme reliability has led to considerable testing of each component or subsystem before it goes aloft, rather than the testing of an occasional sample or an equivalent unit, which would

be scrapped after test. An appreciable part of the lifetime of a unit can be expended during test.

Tests are seldom performed in the combined environment found in space, because of the high cost and complexity of such an operation. Instead one or two environmental elements are provided at a time and, as a result, it is possible to miss some synergistic effect of various combinations.

Vacuum testing itself seldom duplicates the vacuum which the part will actually experience. In most cases of actual operation the pressure will go from sea level ambient to 10^{-9} Torr or less in a few minutes, except in sealed or partially sealed parts of the vehicle. It is only in the last few years that ultrahigh vacuum equipment (10^{-8} Torr or better) has been available with rapid pumpdown. Even now, there are very few test chambers (bell jar size or larger) which can reach 10^{-11}. If slow reduction in pressure is used it is possible that some of the smaller molecules would have time to interact, unlike in space. Also, since vacuum chambers are finite in size, any of the molecules which outgas will find a wall to bounce against, a situation which is not present on the surface of a space vehicle, although it occurs inside of course. This is primarily a problem with lighter molecules; molecules of higher weight and boiling point will condense on the surface of the wall and remain there.

Much valuable information has been obtained by testing in a combination of the anticipated temperature and pressure. Subsequent sections will show clearly why thermal vacuum tests are almost always included in specifications for testing spacecraft components.

Potentially valuable information from radiation-vacuum and radiation-temperature tests is not as available as thermal-vacuum. The testing which has been done has shown that the combination of environmental elements is better in some cases, and worse in others than either element separately. There is no doubt that the test environment may differ from the actual space environment, but by careful planning, tests can be performed which will result in the gathering of invaluable data.

2.3.2 Storage Conditions

For some time prior to launch the spacecraft will undergo fabrication and be stored on earth, and subjected to its atmosphere.

Electron tube manufacturers are well aware of the need for environmental control during fabrication of these devices. The nominal atmospheric composition shown in Table 2-2 of Section 2 is modified by a great deal of water vapor and salt at Cape Kennedy, and thus provides a corrosive atmosphere during storage and prelaunch. In addition to these corrosive effects of sea coast and industrial atmospheres, there are also serious abrasive effects of dust and sand.

A further modification of environment may be provided by the rest of the vehicle. Where there is heat conduction and convection, the temperature of a given part may be altered by the sun's beating down on the craft, or by the storage of liquified gases, the latter, possibly for only a short term exposure.

2.3.3 Sterilization

2.3.3.1 Introduction

At present it is definitely planned to sterilize all vehicles going to Mars, or passing so close to that planet as to make an accidental crash landing possible. There are obvious sound scientific and political reasons for not contaminating this planet with earth organisms which would interfere with observations of the intrinsic nature of Mars and possibly upset the balance of this nature.

The feasibility of sterilizing lunar vehicles has not been completely settled. It seems probable that there were some live earth organisms on both Lunik II and Ranger IV despite sterilization procedures.[45] Whether such organisms could live, grow and reproduce on the moon is doubtful, because of hostile conditions there. Nevertheless the moon should not be contaminated to the extent that life scientists will be unable to determine whether organic structures found on the moon are native to it or were brought by earlier lunar vehicles. It has been calculated that the total weight of viable organisms should be kept below 0.01 gram per flight.

It seems highly improbable that there is danger of microbiological contamination of Venus. The surface is too hot and there is no indication that micro-organisms can multiply in the Venusian atmosphere.

2.3.3.2 Methods of Sterilization

2.3.3.2.1 In-Flight Sterilization - A number of methods have been suggested, all having some serious disadvantages. The first group takes advantage of some feature of the flight. While these methods would, singly or together, kill a number of the organisms, they are not sufficiently effective to render the spacecraft sterile. Ablation, as the vehicle enters a planetary atmosphere and impact, as it hits the surface of the plant, will not produce a total kill. The vacuum of space has been shown ineffective also.(46) The ultraviolet rays will kill a good proportion of the micro-organisms on the surface, but will not reach the interior of the craft. Cosmic rays (1 rad/year) and solar flares (10^2 to 10^4 rads through shielding) are both inadequate for sterilization. If the space craft spent 10 hours going through the Van Allen Belt, it might receive enough radiation to sterilize the surface; but once again, the shielding would prevent a substantial kill on the inside.*

In short, sterilization by launch or in flight seems unlikely. As a matter of fact one could postulate "contamination by launch" instead. While the craft is on the launching pad, it is in contact with unsterile launching support equipment and with air which may contain 1000 organisms per cubic foot.(45)

2.3.3.2.2 Pre-Flight Sterilization - It seems probable that the procedure finally settled upon will have to be

(1) special sterilization environment at some pre-launch period, or

(2) completely aseptic fabrication and transport, or

(3) a combination of these factors.

Such sterilization could consist of heat, ionizing radiation, fumigation, or immersion in an antiseptic liquid. These, too, present serious problems. The heat will damage the electronics; the radiation (at least 1.2×10^7 rads required) will damage plastics and optical properties of glass, even the more resistant ones scheduled for use in Surveyor. The

*Jaffe(45) who quotes this calculation says that the 10 hours will give a dosage of 10^7 rads; however his figure seems very high, since much of the 10 hours would be spent in the milder parts of the Van Allen Belt.

gases, of which ethylene oxide has gotten the most attention, are not proven sterilants and are known to damage some plastics. Liquids are likely to degrade electrical properties of connectors, just as an example.

The completely sterile assembly of an entire spacecraft and keeping it free from contamination after assembly seems to present insurmountable difficulties. However, it is possible that those components which are made under clean-room conditions now, could be fabricated in "clean and sterile" rooms and packaged to prevent contamination during shipping. This type of preventive treatment would be valuable in the cases where the component has a hard-to-reach interior location, or would be ruined by sterilization procedure. The post-assembly sterilization step might possibly be of a milder nature, if this were done.

2.3.3.3 Effect of Sterilization on Electron Tubes

Since it appears that the electron tube will have to endure high temperatures during its operating life and be made of radiation resistant materials to withstand the Van Allen Belt or a nuclear power source, neither heat or radiation sterilization procedures appear to provide serious additional hazards. Sterile fabrication procedures would require upgrading of present clean-room conditions.

The most probable gaseous and liquid sterilants would not affect a sealed inorganic tube itself, but might react with associated organic coatings, potting compounds and wire insulation.

SECTION 3

EFFECT OF ENVIRONMENT ON MATERIALS

3.1 INTRODUCTION

In this section the effects of natural and modified space environments on electron tube materials will be covered. As a guide to designers of space-oriented tubes, two tabulations of relative acceptability for selected tube materials have been prepared. Table 3-1 rates various materials for use in a space environment with a conventional power source vehicle. Table 3-2 similarly rates tube materials for use in a space environment modified by a nuclear power source. These two tables summarize the results of the balance of Section 3 where the test conditions under which these data were obtained are presented in detail. The designer should refer to these later sections to determine compatability with his particular situation. These tables tend to discourage the use of some materials which have been approved elsewhere for space use because of somewhat more severe criteria used here. Specifically, it is assumed here that

(1) The parts must first pass a complete and rigorous testing procedure on earth using equipment now available.

(2) The mission will be lengthy and the target is a 10,000 hour lifetime, or better.

(3) A large and powerful electron tube may not be given as favorable a location in a spacecraft as some other electronic components because of the greater amount of heat generated by it and because it can be built to withstand more severe conditions.

3.2 REMARKS RELATIVE TO MATERIALS EFFECTS DATA

Not all the information sought has been published; some is not published for proprietary reasons while in other cases the tests simply have not been performed. Very little data on material effects is classified, but of the available data, some is of questionable validity. There are, unfortunately, no ASTM or standard reliable test procedures

Table 3-1 - Relative Acceptability of Selected Tube Materials (and Components for Associated Circuitry) Based on Ability to Withstand Space Environment (Conventional Power Source)

MATERIAL	ENVIRONMENTAL ELEMENTS MOST LIKELY TO CAUSE FAILURE OR OTHER APPLICABLE CONSIDERATION
Generally Acceptable	
Refractory metals - tungsten, molybdenum, etc.	
High temperature alloys - stainless steel	
Ceramic (used as rigid structures) - aluminum oxide	Vibration at launch, thermal shock (particularly seals)
Platinum	Combined vacuum and temp. over about 1200°C
Gold	Combined vacuum and temp. over about 800°C
Copper	Combined vacuum and temp. over about 800°C
Silver	Combined vacuum and temp. over about 600°C
Inorganic wire insulation	Temperatures over 540°C
Quartz	Vibration at launch. Micrometeoroids (optical properties)
Conditionally Acceptable	
Require careful evaluation with regard to specific type, design specifications, tube fabrication techniques, etc. In many cases environmental testing is required before specific recommendation can be made. These are used in space vehicles like Surveyor and Telstar, but with some protection.	
Glasses	High temperatures (depends on use), thermal shock vibration. Space radiation of 10^6 or 10^8 rads depending on governing failure criteria, even for cerium containing.
Fluorocarbons	High temperatures (150°C to 250°C depending on particular fluorocarbon). Space radiation over 1 to 8 x 10^6 rads (excellent vacuum and cryogenic properties).
Polyimide (Pyre-ML, H film, Polymer S-P)	Temperatures over 220°C (Pyre-ML) to over 350°C (S-P). Possibly long term vacuum.
Special polyolefins (specially irradiated polyolefins, polyethylene)	Temperatures over 100°C-200°C (depending on type and use), vacuum. Cryogenic temperatures.
Tantalum capacitors	Restriction - may not have silicone seals, contain paper or other materials which gas or evaporate in vacuum.
Specially selected or radiation hardened transistors and diodes (Examples: 2N744, 2N705, 2N1406, 2N797).	Space radiation. Temperatures above 150°C. Heat sterilization. (No one manufacturer invariably makes more radiation tolerant devices than any other. Some will, on special order, make transistors and diodes which are more radiation resistant than equivalent commercial units.) The examples given here are not necessarily the best available, but have been picked at random from a group which gave good results with respect to surface damage when subjected to ionizing radiation.
Generally Unacceptable for Use in Space Environment	
May be superior to above listed for other environments and conditions.	
Most wire insulation (some exceptions shown above)	Vacuum, high or low temperatures, space radiation, sterilization.
Most potting compounds (some exceptions shown above)	Vacuum, high or low temperatures, space radiation, sterilization.
Most paints	Vacuum, high temperature, space radiation, ultraviolet.
Cadmium and zinc	Vacuum, (brass may also be banned because of danger of denzincification).
Paper capacitors - foil capacitors with plastic end seals	Vacuum
Most transistors and diodes (Examples: 2N930, 2N1908, 2N1653)	Space radiation. Temperatures above 125°C or 150°C (radiation data based on limited number of tests). Sterilization.

P-2043

Table 3-2 - Relative Acceptability of Selected Tube Materials (and Components for Associated Circuitry) Based on Ability to Withstand Space Environment which has been Modified by Nuclear Power Source

MATERIAL	ENVIRONMENTAL ELEMENTS MOST LIKELY TO CAUSE FAILURE OR OTHER FACTORS WHICH MAKE IT LESS ACCEPTABLE
Generally Acceptable	
Refractory metals - tungsten, molybdenum,etc.	
Ceramics (except boron and cobalt containing)	Cobalt probably acceptable where induced radio-activity is no problem.
High temperature alloys (except boron and cobalt containing)	
Platinum	Combined vacuum and temp. over about 1200°C
Gold	Combined vacuum and temp. over about 800°C
Copper	Combined vacuum and temp. over about 800°C
Silver	Combined vacuum and temp. over about 600°C
Inorganic wire insulation	Temperature over 540°C
Quartz	Vibration, micrometeoroids.
Conditionally Acceptable	
Require careful evaluation with regard to specific type, design specifications, shielding, fabrication techniques, criteria of failures, etc. In many cases environmental testing is required before specific recommendation can be made. Some of these will be used in SNAP-8, with protection.	
Glasses	Radiation, high temperature.
Polyimides	Temperatures over 220°C-350°C depending on type. Possibly long term vacuum.
Special polyolefines (specially irradiated polyolefines, polyethylene)	Extreme temperature, vacuum.
Tantalum capacitors with hermetic glass seals	
Specially selected or radiation hardened transistors and diodes	
Generally Unacceptable*	
Fluorocarbons	Radiation
Boron-containing materials	Thermal neutrons
Cobalt-containing materials which will be subjected to nuclear reactor tests	Induced radioactivity severely limits post-test examination.
Most wire insulation and potting compounds	Radiation, vacuum, temperature.
Most transistors and diodes	Radiation, and temperature.
Most paints	Radiation, vacuum, temperature.
Cadmium and zinc	Vacuum, and temperature.

P-2043

*Generally unacceptable materials may be excellent for some other environment, however, the amount of shielding and sealing required for protection in combined space and nuclear power source environment is probably so high that it is almost always wiser to substitute a material from the generally or conditionally acceptable lists.

available for determining characteristics of a material under exotic conditions. One worker will report results which are 1 to 3 orders of magnitude different from the results obtained in another laboratory. Analysis of these differences in test results has shown six main categories of possible causes for discrepancies.

(1) Criteria of Failure - The terms "threshold," "moderate," and "severe" damage have only the meaning assigned by the investigator. Further, one worker is concerned about changes in tensile strength and other physical properties, while another tests electrical properties under radiation, vacuum, or extreme temperature conditions.

(2) Identification of Material - In the case of plastics, elastomers, and especially ceramics, generic names, such as epoxy or phenolic, cover materials which vary widely in starting materials, additives, and processing conditions. Also, much of the manufacturing process may be proprietary. Unbiased testing groups tend to avoid trade names in their scientific papers in order to obviate legal problems and the appearance of advertising. The identification problem is less severe with metals.

Manufacturers of components such as transistors and capacitors, ordinarily are not required to report changes of fabrication procedures which will affect performance of their products under extreme conditions. The same part number may be applied to two or more components which are much alike in electrical properties under normal earth-bound conditions, but perform quite differently under radiation or vacuum.

(3) Surface Conditions - In the last few years there has been fairly general understanding that a clean-looking surface may have oxide coatings, adsorbed gases, or other coatings which affect the evaporation rate, friction, etc.

(4) Improper Measurements - Problems of this type include: accurate dosimetry for radiation tests, true measurement of pressure at the critical spot in bell jar vacuum tests, location of the significant area for the thermocouple in friction and wear tests at elevated temperatures, and severe temperature and pressure gradients under extreme conditions and with complex shapes.

(5) Improper Test Conditions - This problem applies particularly to radiation and vacuum tests. In nuclear radiation tests, there is misunderstanding of the difference in damage caused by fast neutrons, thermal neutrons, protons, electrons, and gammas. In vacuum tests, there is misunderstanding of the difference in material behavior at high and ultrahigh vacuum or even of the fact that "high" vacuum is not comparable to the vacuum of space. Fortunately, recent data specify test conditions more adequately than some earlier papers did.

(6) Combined Conditions - "Adding" room temperature radiation tests to simple high temperature tests is seldom adequate for predicting how a material will behave under the combined conditions.

Moderately high temperature can "anneal out" radiation induced defects (epoxy glass laminates and some alloys, for instance). In other cases elevated temperature causes liquefaction or evaporation of the transmutation products from radiation, giving a "multiplicative" rather than additive effect to the deterioration of the material.

The combination of vacuum and nuclear radiation is frequently worse than either separately, but in the case of Teflon the absence of oxygen to catalize the radiation induced reaction makes Teflon substantially better in the combined atmosphere.

3.3 ENVIRONMENTAL EFFECTS - GENERAL

After these preliminary remarks regarding test conditions, it is in order to proceed to a general picture of the effects of natural and modified space environment on electron tube materials. Then each class of materials will be discussed.

3.3.1 Material Pairs

When joining two unlike materials to prevent passage of air or liquid between them, the joints or seals may be mechanical or pressure seals, bonding with an adhesive material, soldering, brazing, or welding. There are additional requirements of compatibility and joinability to consider now.

In the joining process, there may be degradation of the material at the junction; sometimes an adhesive, solder or brazing material is used which is less capable of enduring the environment than the original material pair; frequently the two materials do not

have the same or compatible reactions to changes in environment conditions. All these situations tend to make the seal the weakest part of the structure. For this reason, glass-to-metal and ceramic-to-metal seals are several orders of magnitude less resistant to radiation than either of the members of the pair. During the development of electron tubes compatibility with regard to moderate temperature changes and pressures down to 10^{-6} or 10^{-7} Torr, has been determined, making a considerable body of knowledge available for expansion to cover the new environment. Metal-ceramic seals have been shown to operate well in a nuclear radiation environment which has a flux slightly greater than that estimated for the SNAP-8 payload.

3.3.2 Coatings and Composite Materials

Frequently it is possible to utilize the desirable properties of a material and to minimize its faults by combining it with another material, either in a sandwich or honeycomb format. Protective coatings are put on to waterproof a porous material, to prevent rust or other oxide formation on an oxidizable material, to give desired absorption-emission ratios to the surface of a spacecraft, to provide electrical or thermal insulation, or, occasionally, to provide a path for current flow. The situation can be turned around and a substrate be chosen to give strength or economy. Composite material may consist of a network of some strong material filled with a softer, weaker material which has some other necessary property like lubricity, insulation or low weight. It may be a plastic "filled" with hollow ceramic beads to reduce weight, or glass fiber to give strength, radiation and heat resistance.

Protective coatings and composites find use in electron tube manufacture for the covering of the wires leading to and from the tubes, the associated circuitry, and in heater coatings, cathodes, insulators, and r-f loss materials.

3.3.3 Micrometeoroids

The extent of metal penetration by micrometeoroids appears to be a function of the hardness of the metal. The extent of surface erosion due to bombardment by micrometeoroids appears to be of serious consequence only for optical surfaces and very thin film coatings where erosion of a few Ångstroms thickness of material is important.

Recent Explorer XVI data is being examined carefully to determine how much the weight of the protective armor on vehicles can be reduced. It may be halved. (Editor's note: Nucleonics, 21, # 11, 51 (Nov 1963).)

3.3.4 Vacuum

It can be seen from Figure 3-1 (temperature at which evaporation or other weight loss is significant) that ceramics, glasses, and refractory metals can withstand combined high temperature and vacuum much better than some other metals and plastics. This graph combines data from many different sources. In general, the criteria for significant loss in metals is evaporation of a thickness 10^{-5} cm/year. The figures for polymers are based on 10 percent weight loss per year. The ceramic figures are based on several workers' data using different kinds of measurements where it is recognized that these criteria may not all be equivalent. An evaporation loss which has very little effect on the strength of a structural member, may fill an enclosed space around that member with sufficient gas or deposit to interfere with the electrical performance of an electron tube and thus establish the need for different limits than in the case of the structural member.

3.3.5 Radiation

The bar graphs on radiation resistance of materials (Figure 3-2) must also be looked upon as approximate. Criteria of failure vary widely and an over-simplification has been introduced in breaking the groups down into those which are damaged primarily by fast neutrons displacing atoms in the lattice and those where ionizing radiation of gammas is most important. In semiconductors, for instance, both mechanisms are important, although neither is completely understood at present. Current studies on bulk displacement and surface ionization damages conducted at Bendix Research Laboratories Division are casting light on effects of different types of radiation on such semiconductor devices as transistors and solar cells. Thermal neutrons have not been considered in these graphs, although they are mentioned in appropriate places in the more detailed consideration of each class of material in the following sections.

These figures show that plastics, elastomers, glass, and semiconductors are more likely to present problems with regard to nuclear and Van Allen radiation than ceramics and most metals.

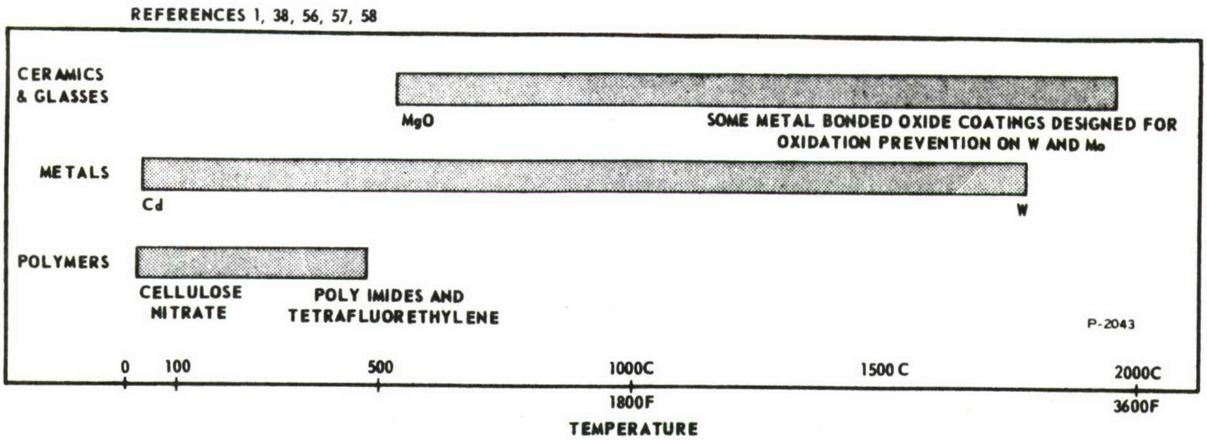


Figure 3-1 - Temperature at Which Evaporation or Other Weight Loss in Vacuum Becomes Significant for Various Classes of Materials

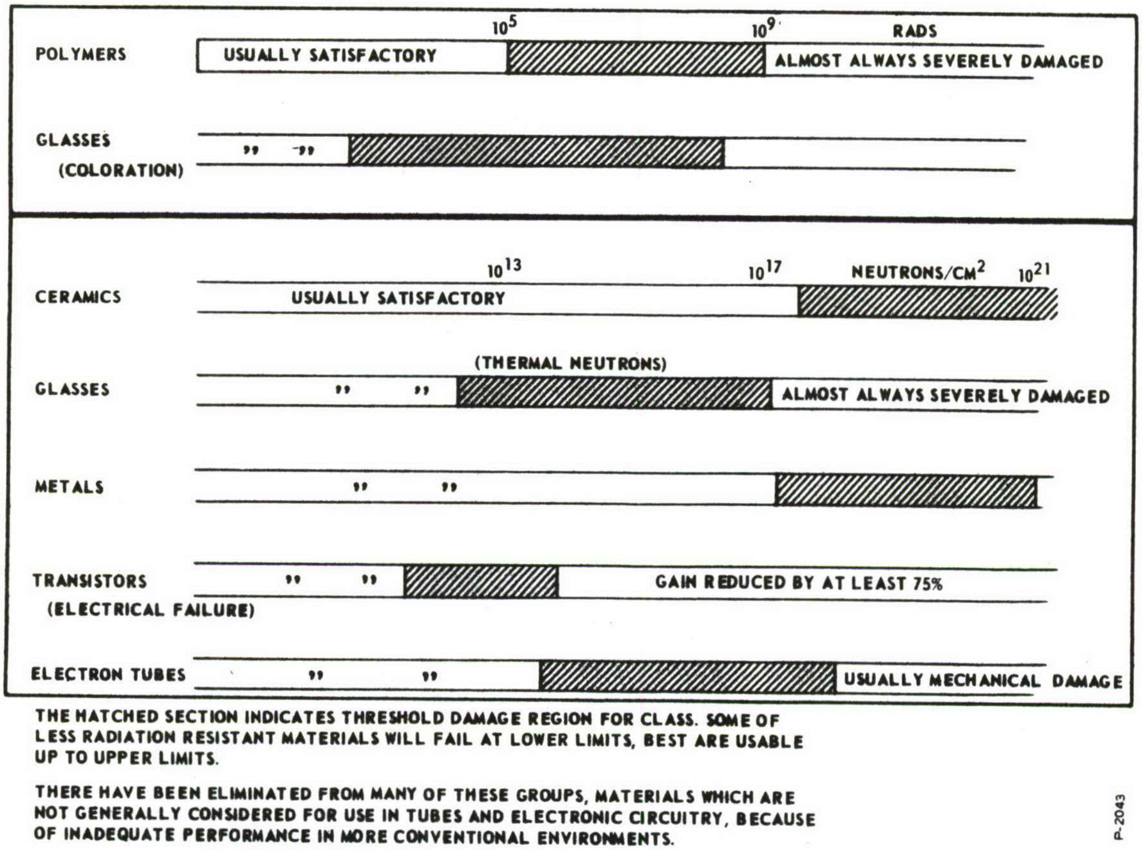


Figure 3-2 - Radiation Resistance of Various Classes of Materials (Based Principally on Damage to Structural Properties)

3.3.6 Ultraviolet

Ultraviolet radiation in space may cause somewhat different damage than UV in air on earth for two reasons.

(1) The atmosphere acts as a filter, removing the lower wavelengths.

(2) Some UV-air damage is really a 2-step reaction, first the interaction of UV with O_2 to form ozone and then the reaction of the ozone with the material being tested.

The effects of combined ultraviolet and vacuum have been studied principally in the cases of thermal control coatings and some glasses. Since only a few materials, notably quartz, are transparent to UV, this form of radiation will not affect materials inside the spacecraft.

3.3.7 Cryogenic Temperatures

It would be difficult to establish orders of merit with respect to behavior at cryogenic temperatures because compatibility of each material with its neighbor in the device (especially in the matter of coefficient of thermal expansion) is as important as the individual material properties. However, it appears safe to say that very few plastics and elastomers are recommended for use at liquid nitrogen temperatures or lower. The few that do not become excessively brittle will be mentioned specifically in the following sections.

3.4 ENVIRONMENTAL EFFECTS ON CERAMICS

Ceramic is here defined as a crystalline oxide or mixture of oxides, thus separating it from the glasses which are amorphous, and the metals and alloys. The definition will be extended to include a few hard-to-classify materials like boron nitride, which is used like a true ceramic in electron tube technology.

In general, ceramics can be used almost as well in electron tubes for space vehicles as for ground based contrivances. Limitations are imposed by vibration during launch and by thermal neutrons if the vehicle has a nuclear power source (boron containing ceramics only).

3.4.1 Vacuum Effects

Ceramics are unaffected by vacuum until very high temperatures are reached. Sublimation rates of some materials are given by Jaffe and Rittenhouse.(4) These are based on the Langmuir equation (see subsection 3.6.1.1) and assume that the mean free path is infinite. In other words it assumes a perfect vacuum but apperas to have a good degree of validity at pressures as high as 10^{-7} or 10^{-8} Torr (Table 3-3).(4)

At the recent International Symposium on High Temperature Technology(47) Steinberg and Kerfoot of Lockheed reported on the behavior of several other ceramic coatings under re-entry conditions, that is, 1 Torr pressure and temperatures from 1000°F to 4000°F. They found that there was substantial evaporation of molybdenum disilicide and columbium disilicide at 2700°F to 2800°F. There is limited evidence to show that a new metal bonded oxide coating for tungsten and molybdenum may have negligible evaporation up to 3600°F (2000°C). All these coatings were developed to prevent oxidation on molybdenum, columbium, and tungsten at the elevated temperatures of re-entry. In these cases, the interest in evaporation rate in vacuum is for the protection of the skin when the returning vehicle gets close enough to earth for the oxygen in the atmosphere to do substantial damage to the bare refractory metals.

Table 3-3 - Sublimation of Some Inorganic Compounds in High Vacuum(4)

Sublimation Rate / Material	Temp. at which given sublimation rate occurs		
	10^{-5} cm/yr	10^{-3} cm/yr	10^{-1} cm/yr
Magnesium Oxide	540°C	730°C	1090°C
Zirconium Oxide	1070	1320	1480
Beryllium Oxide	1340	1480	1700
Thorium Oxide	1400	1600	1900

3.4.2 Radiation Effects

The effect of radiation on most ceramics used in electron tubes is insignificant until exceedingly high doses are received. Several ceramics are rated for radiation resistance below.

3.4.2.1 Alumina

Alumina has been considered a promising material for tube envelopes for some years. Chapin[48] states that alumina has withstood an integrated flux of 10^{20} nvt without undergoing structural change. Schmidt, et al., of General Electric[49] have used alumina in making TIMMS tubes, which can withstand 5×10^7 rads/second (transient) and 3×10^{18} nvt.

3.4.2.2 Sapphire

Sapphire, which is generally considered in a different category than alumina, is really single crystal alumina, which may or may not be doped with another oxide. The colorless transparent sapphire used for scientific purposes normally has a high degree of purity. Table 3-4[50] shows the effect of radiation on thermal conductivity of sapphire, polycrystalline alumina and beryllium oxide. It should be noted that the dosage used is higher than anticipated in electron tubes even in SNAP-8.

In an early study by Wheeler,[51] single crystal sapphire was subjected to a temperature of 350°C and integrated thermal neutron flux of 2×10^{19} nvt. A dimensional change of 0.015 percent was noted as well as a known coloration.

Baicker et al.,[52] recommended the use of sapphire as shielding for solar cells because of a lower tendency to darken than quartz. Telstar I successfully used a 30-mil layer of sapphire shielding.[53] It has been calculated that this shielding

Table 3-4 - Effect of Radiation on Thermal Conductivity[50]

Material	Initial Thermal Conductivity[a]	Exposure I[b]	Thermal Cond. after Exp I[a]	Exposure II[b]	Thermal Cond. after Exp II[a]
Sapphire	600 ± 200	6×10^{19}	300 ± 60	6×10^{20}	200 ± 30
Sintered Alumina	400 ± 100	3×10^{19}	230 ± 40	4×10^{20}	90 ± 5
Beryllium Oxide	600 ± 200	7×10^{19}	400 ± 100	---	---

P-2043

[a] $\times 10^4$ cal/°C cm sec [b] fast neutrons/cm^2

reduced the proton damage by a factor of 200, although the reduction of damage due to electrons was much less.

3.4.2.3 Beryllium Oxide

Beryllium oxide's physical properties will not be affected by the amount of radiation likely to be found near the electron tube even with a nuclear reactor. At an exposure of 10^{21} n/cm^2 (neutrons per square centimeter), it has been found[54] that 23 cm^3 of helium per cm^3 of beryllium were formed in the pure beryllium metal. This gas remains in solution at temperatures lower than 500°C but at high temperatures bubbles form, leading to swelling, embrittlement, and increased gas permeability. Thermal conductivity changes with radiation for the oxide will be found in Table 3-4.[50] More recent data on thermal conductivity of beryllium oxide was obtained by Cooper, Palmer and Stolarski.[55]

Figure 3-3a[55] shows change in conductivity between unirradiated material and that which received doses of 1.5×10^{19} nvt at 70-80°C, 1.2×10^{20} nvt at 80-100°C, and 4×10^{20} nvt at 70-80°C. This is close to the temperature at which one would expect maximum damage.

For comparison a group of samples was irradiated at 500 and 600°C. Figure 3-3b shows that the decrease in conductivity is much less.[55]

3.4.2.4 Boron Nitride

The use of boron nitride near a nuclear reactor will lead to difficulties. Boron has a large capture cross section, or one might say, a large affinity for thermal (and fast) neutrons. Some 18 percent of the boron atoms can be "split" into beryllium and hydrogen. This reaction is primarily a surface phenomena. The hydrogen will outgas; the beryllium conducts electrically, heat is evolved and the physical strength of the boron nitride decreases. Thus, except where it is needed as a modifier (neutron absorber), boron and its compounds are not used near a reactor.

3.4.2.5 Thoria

Thoria has a small capture cross section and the probability of radiation induced reaction in tubes is extremely low.

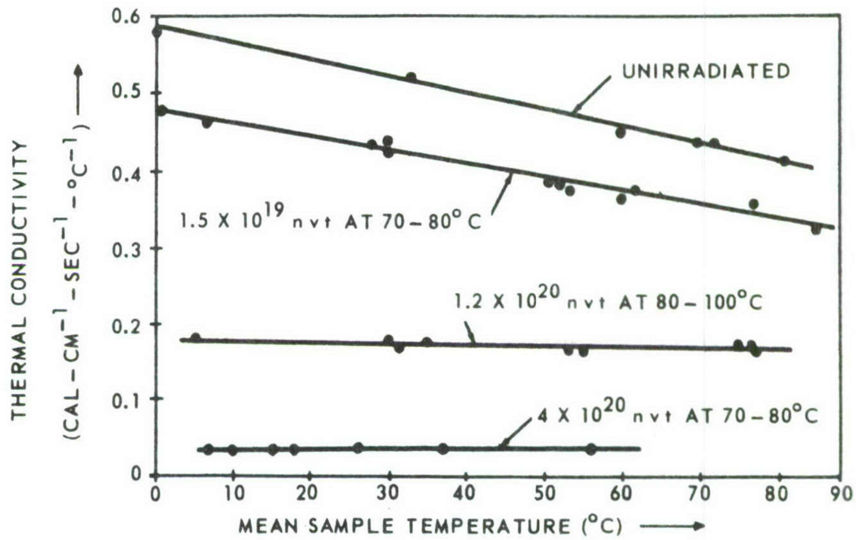


Figure 3-3(a) - Thermal Conductivity of Unirradiated and Irradiated Beryllium Oxide(55)

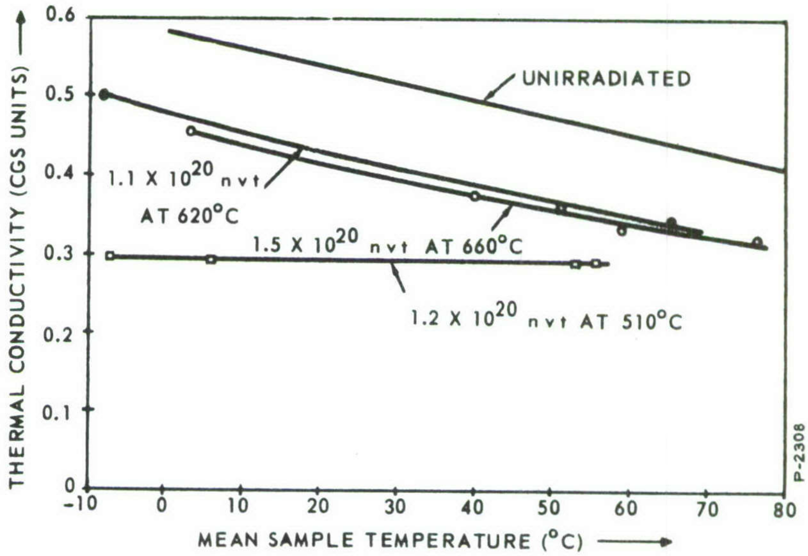


Figure 3-3(b) - Thermal Conductivity of Beryllium Oxide Irradiated at High Temperature(55)

3.5 ENVIRONMENTAL EFFECTS ON GLASSES

In general, the use of glass is not recommended where temperatures will be very high or radiation intense. The softening temperatures of various glasses range from 1075°F for a high-lead lead silicate glass to 1670°F for an alumino-silicate. The softening temperatures of quartz, fused silica, or 96 percent silica are substantially higher, being in the neighborhood of 2800°F.

3.5.1 Vacuum Effects (Combined with Ultraviolet)

It is not anticipated that the vacuum of space in itself will have adverse effects on glass.

The combination of vacuum and ultraviolet radiation was studied by Wahl, Lapp and Haas[56] whose vacuum was measured to be $6 \pm 3 \times 10^{-6}$ Torr. The total energy of the light was 2 pyrons and the wavelengths between 2500 and 7000 Å. This is twice the energy of the same spectrum in space. (The solar constant, 2.0 gram-cal/cm^2/min or 2 pyrons or 140 milliwatts/cm^2, to give it 3 of the conventional sets of units, is defined as the rate at which energy is received from the sun upon a unit surface perpendicular to the sun's rays above the earth's atmosphere at its mean distance from the sun. Of these 2 pyrons, 0.2 percent is of wavelength less than 2000 Å and 51 percent above 7000 Å.)

Wahl, et al.,[56] found that after 100 hours of these conditions, neither fused silica nor aluminum-silica glass were visibly affected. The spectrophotometer recorded no change in transmittance over either UV or visible range.

3.5.2 Radiation Effects

3.5.2.1 Glass Coloration

Among the problems caused by ionizing radiation is the browning of glass due to formation of color centers, a phenomenon that can be found in glasses exposed to the Van Allen Belt as well as to nuclear reactors. The camera lenses in satellites use glass to which a few percent of a cerium compound has been added. Bishay[57] states that the scavenging role of cerium can be explained on the basis of a change in oxidation state from Ce^{3+} to Ce^{4+} as a result of gamma irradiation. Price, Gaines, Newell, and Pearson[58] state that 10^6

rads will result in the loss of a few percent of the total transmission for cerium glass and that even at 10^8 rads there is only a tolerable amount of browning. With non-cerium containing glass the coloration fades some hours after irradiation. Reactor tests with 7720 glass (boron containing) showed discoloration at 10^{12} $nv_o t$ (thermal neutrons).[48]

There is also a change in the electrical resistance of glass with radiation. Yamamoto and Tsuchiya[59] found that with cobalt 60 as a source, the resistance of high density glass decreased until a dose of 10^6 rads was reached and then increased. Cerium-containing medium density glass had no such minimum point. This is shown in Figure 3-4.[59]

In conventional tube fabrication, pyrex glass, which contains 10 to 15 percent boron, is often used. As was mentioned in subsection 3.4.2.4, the use of boron near a nuclear reactor, except as a radiation modifier, is highly inadvisable. The mechanical damage due to 10^{15} $nv_o t$ or greater radiation shows itself in the form of cracks in the glass and rupture of metal-to-glass seals.

Several tests have shown the effect of boron content on glass behavior.

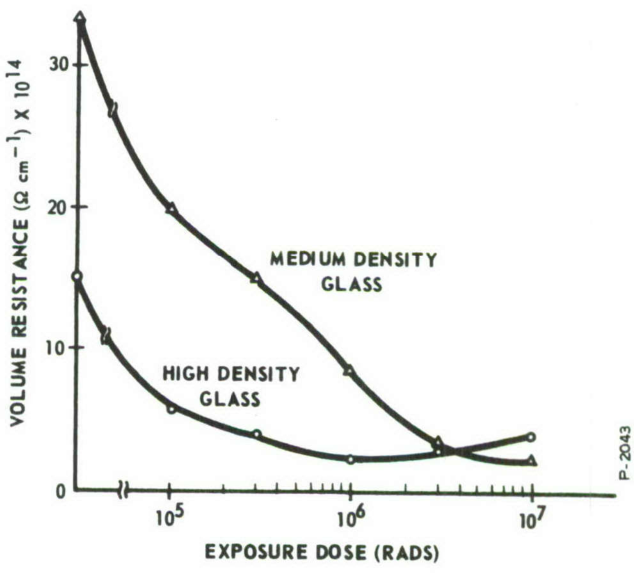


Figure 3-4 - Resistance of Glass to Nuclear Radiation[59]

Tests on evacuated glass (Corning 7720) envelopes with and without base pins showed gas formation at 10^{16} n/cm^2; the internal pressure increased from 10^{-6} to 10^{-4} Torr, according to data[48] summarized by Battelle's Radiation Effects Center. At 10^{17} $nv_o t$ another test on the same glass showed cracking on all specimens. Further exposure resulted in fragmentation.

Another glass, Corning 7070, containing 28 percent boron oxide, was completely disintegrated by an integrated dose of 2.5 x 10^{16} n/cm^2.

To show that glass with low boron content is less affected, 13 glass envelopes made of Corning 0120 and equipped with base pins, were irradiated in the Brookhaven reactor. After exposure to an integrated flux of 2 x 10^{17} n/cm^2, the envelopes were examined and found to be discolored. No fissures or cracks were found.

J. D. Fleming[60] has reported on effects of irradiation on slipcast fused silica. His samples were kept in the Westinghouse Testing Reactor for 340 megawatt days. He concluded that irradiation to doses up to 4 x 10^{20} nvt cannot be said to cause a statistically significant change in strength.

3.5.2.2 Quartz

E. V. Kolontsova and I. V. Telegrina[61] discuss changes in crystal structure of quartz which appear after exposure to 10^{19} neutrons/cm^2. The Laue pattern and diffuse maxima obtained by X-ray diffraction show that a β transition or reorientation starts to take place about 10^{19} neutrons/cm^2; and by 7 x 10^{19} neutrons/cm^2, there is a substantial change in the diffraction pattern. While the authors do not apply their findings to electron tubes, it seems safe to say that such a change in crystal structure would set up severe strains, especially where the quartz was joined to an unlike material. Fortunately 10^{19} neutrons/cm^2 seems well above the dosage anticipated for electron tubes and phase transformations in quartz may be ruled out as a potential problem source.

Fused silica is transparent to ultraviolet.

3.5.2.3 Tube Tests

Tests which have been performed on completed tubes have shown failures at fluxes as low as 2.3×10^{14} $nv_o t$. (Two 4J52A magnetrons developed gassiness and cracks at this level in tests by Admiral.) Pfaft[62] has indicated that the damage is also a function of tube design. He found that BL800A reflex klystrons, 3D21B modulators, 3CX100A5 ceramic Hi-mu (UHF) triodes survived a dosage 1×10^{16} nvt and 4.5×10^6 rads, while all the unshielded 3E29 dual tetrodes suffered glass envelope fracture and one of 3 5727/2D21W thyratrons failed to ionize after 160 hours in the same test.

A summary of the radiation resistance of ceramics and glasses is shown in Figure 3-5.

3.6 ENVIRONMENTAL EFFECTS ON METALS

3.6.1 Structural Metals

3.6.1.1 Vacuum Effects

While metals are not ordinarily thought of as volatile, still in the vacuum of space some will sublime at an appreciable rate. Cadmium and zinc, which are used on earth for sacrificial corrosion protection over steel, are banned for many space vehicle uses because they tend to evaporate. This action may have several ill effects:

(1) The damage to the part which was made of or coated with cadmium or zinc because of loss of material.

(2) The pollution of an enclosed space with the metal fumes.

(3) The damage to other and cooler parts on which the metal may condense, thus providing a conducting path on an insulator or interfering with the optics of a quartz lens or the reflectivity of a thermal control coating.

The loss of metal can be predicted if the temperature of the metal is known. The Langmuir equation has been used by a number of workers including Jaffe and Rittenhouse[4] to calculate sublimation rates

$$W = \frac{p}{17.14} \sqrt{\frac{M}{T}}$$

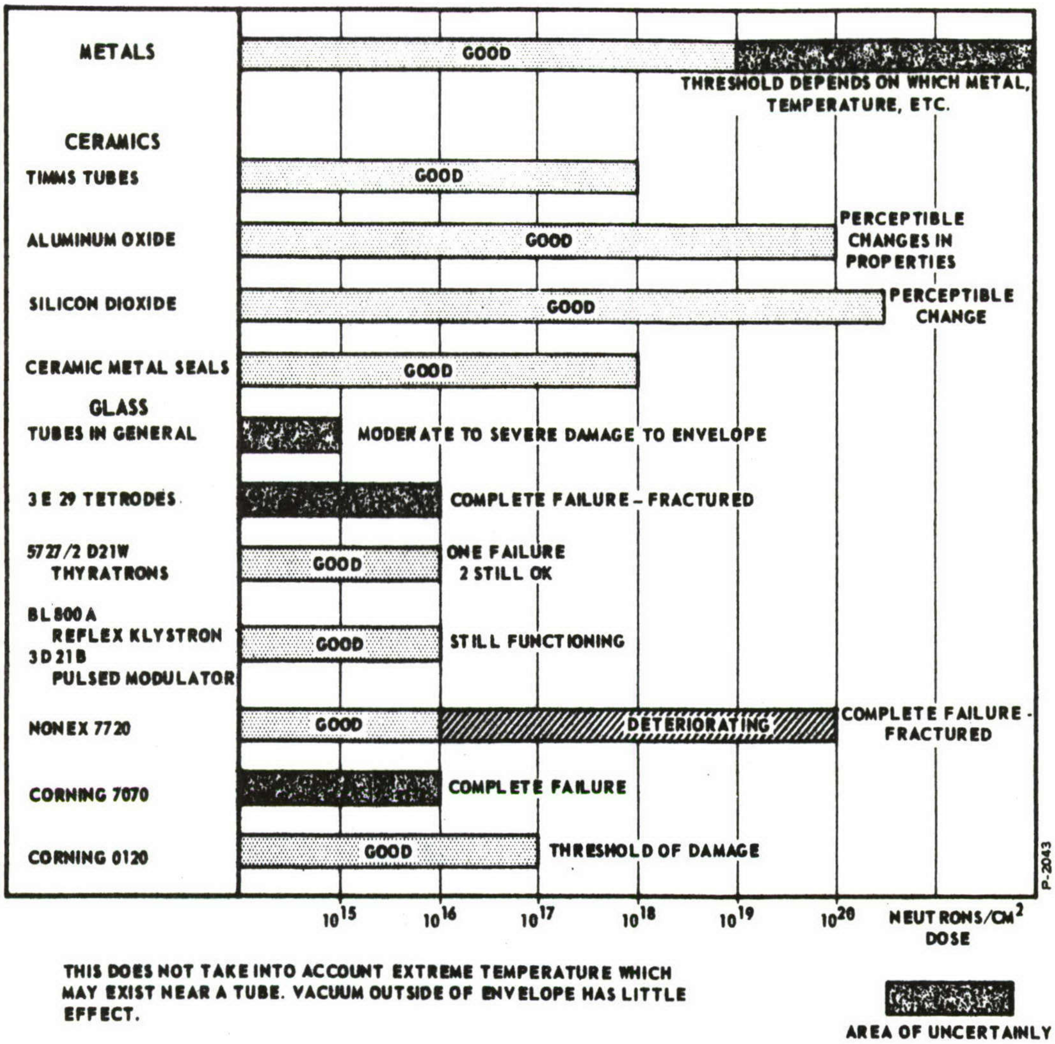


Figure 3-5 - Relative Resistance of Tube Envelope Materials to Radiation from a Nuclear Power Source

where

W = rate of evaporation in g/cm^2-sec

p = vapor pressure of material in Torr

M = molecular weight in the gas phase

T = temperature in degrees Kelvin

or

$$S = 1.85 \times 10^{6} \frac{p}{\rho} \sqrt{\frac{M}{T}}$$

where

S = rate of sublimation in cm/yr

ρ = density of solid material in g/cm^3

Experimental verification of these values requires ultrahigh vacuum equipment and sensitive microbalances operating in vacuo. Even so, Buckley and Johnson[63] have been able to show that zinc obeys the Langmuir equation reasonably well.

Table 3-5[4] shows the sublimation rate of many of the metals which are used in electron tubes.

Table 3-5 - Sublimation Rate of Selected Metals at Elevated Temperatures in Vacuum[4]

Element	Temperature at which the sublimation rate is					
	10^{-5} cm/yr		10^{-3} cm/yr		10^{-1} cm/yr	
	°C	°F	°C	°F	°C	°F
Manganese	450	840	540	1010	650	1200
Silver	480	890	590	1090	700	1300
Aluminum	550	1020	680	1260	810	1490
Copper	630	1160	760	1400	900	1650
Gold	660	1220	800	1480	950	1750
Chromium	750	1380	870	1600	1000	1840
Iron	770	1420	900	1650	1050	1920
Nickel	800	1480	940	1720	1090	2000
Titanium	920	1690	1070	1960	1250	2280
Platinum	1160	2120	1420	2580	1640	2980
Molybdenum	1380	2520	1630	2960	1900	3450
Tantalum	1780	3250	2050	3700	2300	4200
Tungsten	1880	3400	2150	3900	2500	4500

P-2043

3.6.1.2 Radiation Effects

3.6.1.2.1 Discussion - Common structural metals have been used in reactors for 20 years and have demonstrated great radiation resistance, far beyond that of plastics, elastomers, semiconductors and glasses. Steels, stainless steels, nickel, niobium and zirconium alloys have been studied to determine limitations. Generally, under reasonable temperature ranges, the effects of reactor radiation on structural metals consists of an increase in tensile and yield strength, hardness and reduction of elongation and ductility. However, such effects do not show up until an exposure of at least 1×10^{19} neutrons per square centimeter have been achieved. Type 347 stainless can be used at doses as high as 10^{22} n/cm^2, according to Shober and Murr.(64) At higher temperatures, 600°F and up, the tendency toward becoming harder and stronger is offset by the annealing effects of the temperature.

Speaking at the same ASTM meeting as Shober, and Murr, N. E. Hinkle of Oak Ridge(65) showed that only small changes in rupture strength occurred to stainless steel at 1300°F to 1500°F, to niobium - 1 percent zirconium at 1800°F and to zircalloy 2 at 700 to 900°F. Inconel 600 lost 25 percent of its rupture strength at 1500°F, possibly in part because of the boron impurity. In general, cold - worked alloys are less affected than others.

In REIC Report 20, "Effect of Nuclear Radiation on Structural Metals,"(54) a few limitations are indicated. For instance, at -423°F types 301 and 310 stainless steel lose 27 and 10 percent respectively, of their ultimate tensile strength with a fast neutron (greater than 0.33 mev) dose amounting to 2×10^{17} n/cm^2. A post-irradiation anneal can embrittle type 347 stainless, possibly because the columbium carbide, normally present, dissociates during extensive radiation and then recombines near grain boundaries during annealing. Boron, even when present as an impurity, impairs ductility and rupture life of Inconel, if the dose is large enough. The mechanism suggested is that hydrogen, one of the fission products of boron, may diffuse to the grain boundaries.

At doses of 1×10^{21} n/cm^2 beryllium behaves similarly, yielding 23 cc helium per cc Be. The gas remains in solution at less than 500°C, but forms bubbles at higher temperatures leading to swelling, embrittlement, and increased gas permeability.

The refractory metals molybdenum, niobium and tantalum have been tested after doses of 10^{20} n/cm^2 without finding any changes other than increases in yield and tensile strength and reduction of elongation and ductility similar to stainless steel.

Copper, which is used not only for its structural properties, but also its electrical characteristics, is strengthened by irradiation. High temperature anneals out this effect. The change in conductivity is less than that of platinum, silver, and bismuth, a damage rate of 1×10^{-26} ohm cm/n/cm^2 having been observed after a radiation dose of 4×10^{17} n/cm^2.

There is no evidence to show that the precious metals are less radiation resistant than the more common structural metals, with the exception of silver which has an appreciable capture cross section. The cross section is less than that of cobalt.

3.6.1.2.2 Cobalt - The use of cobalt and its alloys in nuclear-powered equipment is usually banned because of induced radioactivity and long half life of cobalt 60. While the induced radioactivity might not cause a problem in an unmanned vehicle which was not returning to earth, there remains the problem of component preflight testing on earth. In a tube which contains cobalt it would take months, or possibly years, before it could be handled by anything other than extreme remote control equipment.

Radiation effects upon magnetic materials are discussed further in subsection 3.6.2.2 and the cobalt magnets do not appear to suffer adversely from induced radioactivity.

3.6.1.2.3 Summary - It might be reiterated here that no electron beam device will receive anywhere near the dosage discussed in the preceding paragraphs as being sufficient to cause changes. Therefore, from the radiation point of view, any conventional structural metal, with the exception of cobalt-containing alloys, may be used safely. This approved list included OFHC copper; tungsten; niobium; molybdenum; stainless steel; tantalum; manganese; titanium; alumina; and the precious metals, gold, silver, and platinum. Cobalt-containing alloys will not be appreciably affected by Van Allen or Starfish Belts.

3.6.1.3 Other Hazards

The data on Micrometeoroid damage to metals is shown in subsection 2.1.4. Electromagnetic radiation will cause no difficulty to structural metals themselves, although it may affect thermal control coatings applied to them.

Temperature considerations may be influenced much more by the heat generated in the electron beam device than any other factor. The difficulty in dissipating heat in a vacuum will be discussed at greater length in another section. It should be sufficient to say here that metals like silver, copper, and gold which have appreciable vapor pressures in vacuum at temperatures of 500, 650, and 700°C should be evaluated carefully in the light of anticipated operating temperatures.

3.6.2 Magnetic Materials

3.6.2.1 Vacuum Effects

The sublimation rates of metals (Table 3-5)[4] indicate that it is very unlikely that a magnetic material would fail because of the vacuum environment.

3.6.2.2 Radiation Effects

Gordon and Sery of U.S. Naval Ordnance Laboratory have studied this subject intensively, and have published a dozen papers on the subject. The data here is based on two of their papers[66,67] both of which review their own and other workers' findings.

It has been shown that, with irradiation of 10^{17} epicadmium neutrons/cm^2, materials with coercive forces greater than 0.5 oersted (such as silicon irons, aluminum irons, and Permendur) generally exhibit no appreciable changes in any of their magnetic properties. However, materials with coercive forces of less than 0.5 oersted (supermalloy, 4-79 Mo permalloy, and other nickel-irons) show drastic degradation in their structure sensitive properties (coercive force, permeability, and remanence). Supermalloy and 4-79 Mo permalloy show major changes at as low a dose as 10^{16} neutrons/cm^2.

The recent interest in space radiation has encouraged investigation of the effects of protons on magnetic materials.

Pure iron and 5-79 Mo permalloy were irradiated with 1.5 and 4 mev protons up to 10^{16} and 10^{17} protons/cm^2 at 100°C. There were no changes in coercive force, initial permeability, saturation magnetization, or magnetic anisotropy. Remanence and magnetic permeability decreased about 35 percent for permalloy and 10 to 20 percent for iron. Two percent silicon iron gives a magnetization similar to pure iron. Recovery of initial values began to appear after annealing iron at 150°C to 200°C and complete recovery occurred after a 500°C anneal. Permalloy had to be annealed after irradiation in precisely the same manner as its original pre-irradiation heat treatment to get back to original values.

Figures 3-6 to 3-9 are taken from Gordon's paper. Figure 3-6 shows the effects of radiation (neutrons) on open[(67)] circuit inductance, Figure 3-7[(67)] shows the changes in the hysteresis loop due to proton irradiation of 5 Mo permalloy. Figures 3-8[(67)] and 3-9[(67)] show effects of proton irradiation on pure iron.

These illustrate the point that radiation damage in magnetic properties is roughly inversely proportional to the number of imperfections in the original crystal lattice. This is parallel to the case with semiconductors where electronic properties of intrinsic materials show a larger percentage change upon irradiation than highly doped material. This is because in each case the radiation produces vacancies and interstitials, which are not substantially different from imperfections produced by other means. Coercive force is proportional to crystal imperfections.

In summary, Table 3-6[(67)] gives a guide to choosing magnetic materials for high temperature and high radiation environments.

3.6.3 Brazing and Sealing

3.6.3.1 Brazing and Sealing Materials

High temperatures and heat dissipation problems will eliminate many combinations of materials as well as some conventional methods for joining electron tube parts. Welding and brazing techniques will no doubt be employed. Table 3-5[(4)] refers to some of the metals used in brazing. It can be seen that most good high temperature brazing materials are also entirely satisfactory for use in vacuum and radiation environments.

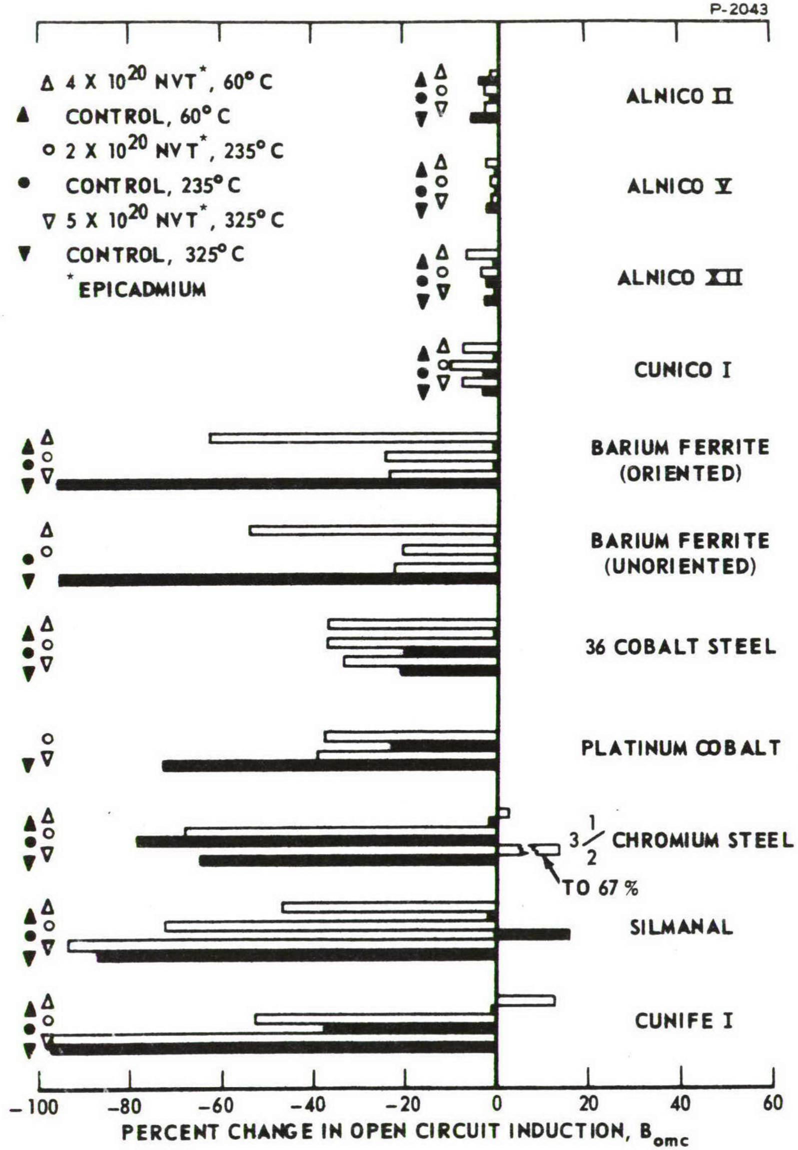


Figure 3-6 - Effects of Radiation on Open Circuit Magnetic Induction. Permanent Magnets Irradiated to 10^{20} Epicadmiun Neutrons/cm^2 (67)

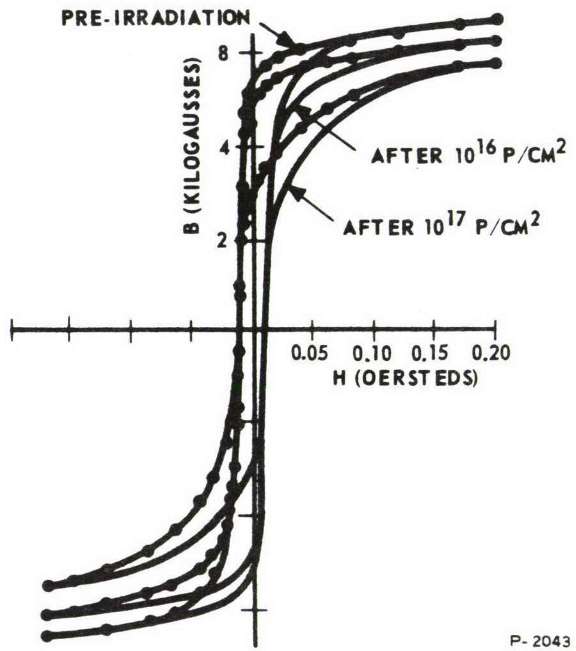


Figure 3-7 - Proton Irradiation of 5 Mo Permalloy Effect on Hysteresis Loop of Bombardment with 10^{16} and 10^{17} Protons/cm^2 (1.5 Mev) (67)

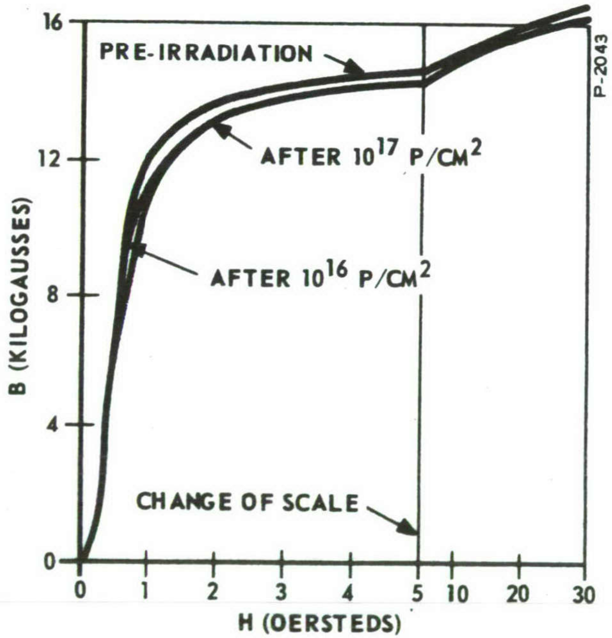


Figure 3-8 - Proton Irradiation of Pure Iron: Effect of Magnetization Curve of Bombardment with 10^{16} and 10^{17} Protons/cm^2 (1.5 Mev)(67)

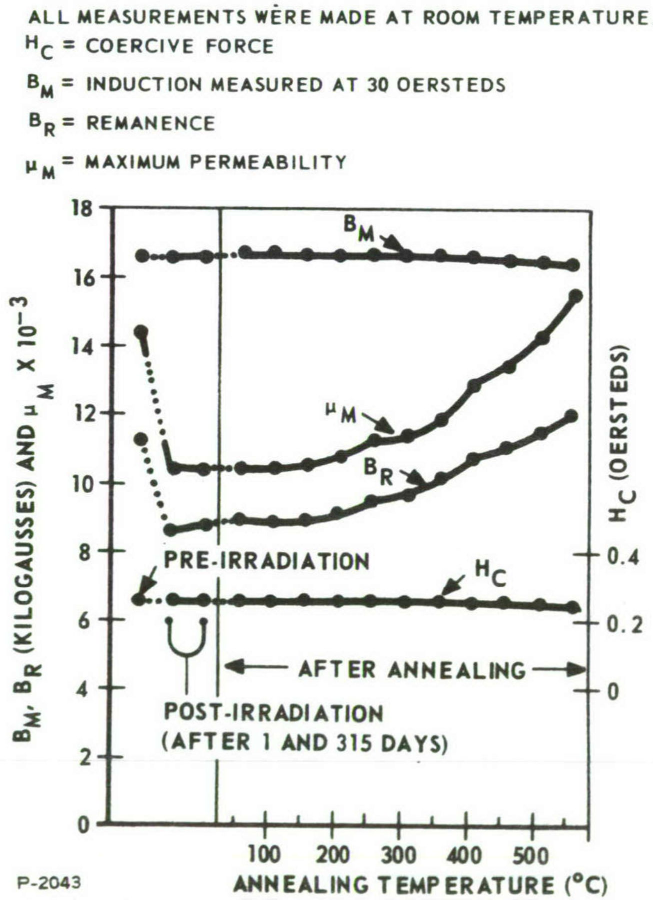


Figure 3-9 - Recovery Curves for Pure Iron: Effect on Magnetic Properties of Irradiation with 10^{17} Protons (1.5 Mev), Post-Irradiation Storage at Room Temperature, and Isochronal Annealing in 50°C Steps for One Hour Periods(67)

Table 3-6 - Guide to Utilization of Magnetic Materials in Hyper-Environments(67)

Permanent Magnet Material	Radiation Stability 10^{16} fast nvt	Temperature Stability 500°C	Probable Stability in Combined Environment
Alnico 5	VG *	VG	VG
Alnico 6	- *	VG	VG
Alnico 2	VG *	G	G
Alnico 3	-	G	G
Alnico 1, 4, 7	- *	U	U
Remalloy	-	U	U
Indalloy	-	U	U
Vicalloy	-	U	U
0.9 Carbon Steel	-	U	U
Alnico 12	VC *	NU	NU
Tungsten Steel	-	NU	NU
Chrome Steel	VG	NU	NU
Cobalt Steel	VG *	NU	NU
Cunife 1	VG	NU	NU
Cunico	VG *	NU	NU
Barium ferrite	VG	NU	NU

P-2043

VG = very good
* = becomes radioactive
U = usable
NU = not usable

The big exceptions are cobalt containing alloys, where induced radioactivity limits reactor testing and boron containing materials where transmutations, outgassing, and heating caused by thermal neutrons make the material unsuitable for use in nuclear-powered vehicles.

3.6.3.2 Metal-Ceramic and Metal-Glass Seals

Some of the text in the sections on ceramics and glass has already indicated that seals are usually weaker than either of the materials which are joined. The radiation resistance, as measured by the dosage required to crack the seal, is usually about two orders of magnitude less than the "threshold damage dosage" quoted for the more sensitive material of the pair.

3.7 ENVIRONMENTAL EFFECTS ON DIELECTRICS

For ease in discussing the wide variety of materials used as dielectrics, they are here divided into two classes.

(1) Organic and Silicone Polymers - This includes plastics and elastomers, the phenolics, epoxies, polyethylenes, fluorocarbons, urethanes, synthetic rubbers, etc. While silicones are not technically true organics, that is, they do not have carbon "backbones," they do have methyl and phenyl groups branching off the Si-O-Si-O backbone and behave much like organic polymers. As the name indicates, an elastomer is an elastic rubbery material; a plastic is comparatively rigid. As a class, polymers are more temperature sensitive than any other class of materials discussed in this report.

(2) Inorganic Materials, Except Silicones - These are primarily ceramic-type materials, usually oxides. They normally can withstand higher temperature, but are brittle.

Dielectrics are used as wire insulation and potting compounds. They frequently are used to support, as well as to insulate, electronic components. It is frequently necessary that they help dissipate heat as well, a function for which they generally are not very suitable. Polyurethane foam, for instance, is one of the best thermal insulators known.

3.7.1 Organic and Silicone Polymers

The chemical reactions involved in making polymers are of little concern here, but a few remarks on the chemical structure of the commercial polymers may be helpful.

The simplest form is the repetition of one monomer to form the long-chained polymer, as with polyethylene. A more complex form has two groups which repeat over and over as with polyesters. In any event, there is a wide variation in the molecular weights inside any batch because of variation in the number of times the monomer repeats to form the molecule, even with identical processing conditions. As might be anticipated the shorter molecules are more volatile than the longer ones. Beside the basic material, there may be small amounts of other organic materials added to improve oxidation resistance,

ductility and other qualities. Pigments may be added to give color, or glass fibers to give strength. Hollow glass microspheres reduce weight. In addition, there may be some unreacted catalyst or monomer in the finished product. Differences in processing techniques lead to differences in physical properties even with the same raw ingredients, either because of differences in molecular weight distribution or because of a greater or lesser tendency for sidebranches to form and cross linking to occur.

The above remarks explain, at least in part, why there is such variation and uncertainty about polymer properties. It may be added that the complexity of complete chemical analysis of polymers helps the manufacturer keep his proprietary secrets. This is quite unlike the metal industry, where routine analysis, metallographic cross section and some thoroughly standardized physical testing readily identify an alloy.

3.7.1.1 Vacuum Effects

Because the polymer is not a single molecular species, the Langmuir equation cannot be used to predict its rate of evaporation. Furthermore, the evaporation tends to be selective, i.e., the shorter molecules and volatile addition agents sublime first, leaving a material which may have somewhat different physical properties than the original. It may become porous, harder or more brittle.

Wire coatings recommended recently for use in the vacuum of space include specially irradiated polyolefins, fluorocarbons and polyimide coated fluorocarbons. The first is an excellent example of using ionizing radiation to manufacture a product.

The irradiated modified polyolefin described in Lanza and Stivers paper[68] (trade name Novathene, Mfr. Raychem Corp.) has been designed for space used by substituting low-volatility additives for those which outgas badly and using a high molecular weight polymer system. Thus, the material has the radiation resistance of polyethylene without the high volatility which makes the latter inappropriate for extended use in vacuum. The authors claim the weight loss in vacuum to be comparable with that of Teflon. The radiation resistance is much better than Teflon. The threshold of damage to elongation properties is about 500 megarads, while Teflon loses 88 percent of its elongation at 8 megarads in vacuum and suffers serious damage at

1 to 2 megarads in air. The electrical properties of the polyolefin are not affected by 2000 megarads. In general, electrical insulation properties of wire coatings are less affected than physical properties. However, increasing brittleness and resulting breaks in insulation effectively negate the value of the insulation properties which may remain.

Lanza and Stivers also tested corrosivity of their material. The breakdown products caused slight pitting in a copper mirror when mirror and polyolefin were subjected to 100 megarads. This, they claim, is less than corrosion damage attributable to the fluoride breakdown products of fluorocarbons.

Klass[69] summarizes work presented by H. S. Adams of Hughes Aircraft at The Electronic Components Conference in Washington in 1963. Hughes, which holds contracts for part of the Surveyor, was looking for wire insulation which could withstand modified lunar and space conditions. The wire was going to be shielded against space radiation and the temperatures were calculated to vary from -300°F to +280°F. Their vacuum test equipment went down to 10^{-7} Torr. They tested an FEP Teflon coated with a modified polyimide (Surok, made by Suprenant Division of International Telephone and Telegraph), TFE Teflon and an irradiated polyolefine (trade name not stated). They found the first named had the best combination of properties.

An anonymous duPont article[70] points out that Teflon was used successfully for wire insulation on Tiros, even outside the spacecraft. It is also used for dielectric shields for isolation components, wrappings for cable bundles, cable clamps, bearings, washers, sliders, feedthrough insulating sleeves on the antennas, coax cable insulation, etc. Comparison was made with irradiated modified polyolefin (no trade name given), silicone rubber (no trade name given) and "Teflon: FEP -- Pyre M. L." (presumably Surok).

Of particular interest were the mass spectrograms of gases evolved from both kinds of Teflon at 100°C and 10^{-7} Torr. They indicated that the gases were adsorbed air and not breakdown products of Teflon.

Table 3-7[69,70] combines the data on volatility obtained by Hughes and duPont.

Table 3-7 - Insulation Weight Changes in Vacuum (10^{-7} Torr)[69,70]

Sample	Percent Weight Change			Temperature at which Outgassing was Noted (°C**)
	100 hours at 100°C *	100 hours at R.T.*	168 hours at 125°C**	
Teflon TFE	0.04	0.01	none detectable	300
Teflon FEP	0.08	0.04	-	-
Irradiated Modified Polyolefin	-	2.2	0.23	193
Silicone Rubber	-	5.2	-	-
Teflon FEP--Pyre ML (or Surok)	0.15	-	0.5	260
Polyvinyl Chloride	-	3.6	-	-

P-2308

*DuPont data. **Hughes data.

Table 3-8 - Circuit Board Weight Changes in Vacuum (10^{-6} Torr)[56]

Material	Percent Weight Change 1000 Hours at Room Temperature
Polyesters	0.02 and 0.03
Phenolics	0.09 and 0.08
Epoxy	0.0 0.0

P-2308

Wahl and his coworkers[56] found that glass laminates of the type used for circuit boards (polyesters, epoxy, and phenolics) suffered little, if any, loss in weight after exposure to 1000 hours of vacuum at room temperature (Table 3-8).[56]

These specimens were "conditioned" by heating in an air oven at 210°F before test. This would not remove all the adsorbed gases, as a vacuum bakeout would.

Podlaseck and Sukorsky report[71] that certain plastics lose weight faster at normal atmospheric pressure than at lower pressures when temperature is raised to the point where oxidation reactions would normally proceed at a significant rate. These include

some phenolics, epoxies, dially phthallates and silicones. Thus because vacuum serves as an inert environment, the upper temperature limit for use of these plastics may be extended in vacuum.

A summary of earlier data on weight losses suffered by polymers is given by Jaffe and Rittenhouse.[4] Table 3-9[4] gives some of these figures, which are expressed in temperature at which a 10 percent weight loss in vacuum may be expected.

Table 3-9 - Decomposition of Polymers in High Vacuum Temperature for 10 Percent Weight Loss Per Year in Vacuum[4]

Polymer	°C	°F	Quality of Data*
Nylon	30 to 210	80 to 410	A
Polyester	40 to 240	100 to 460	B to C
Epoxy	40 to 240	100 to 460	B to C
Polyurethane	70 to 150	150 to 300	C
Neoprene	90	200	C
Methylmethacrylate	100 to 200	220 to 390	A
Isobutylene isoprene (butyl rubber)	120	250	D
Polystyrene	130 to 220	270 to 420	A
Phenolic	130 to 270	270 to 510	B to D
Polypropylene	190 to 240	370 to 470	A
Natural Rubber	190	380	B
Silicone Rubber	200	400	D
Ethylene terephthalate (Mylar, dacron)	200	400	A
Polyethylene (low density)	240 to 280	460 to 540	A
Chlorotrifluoroethylene	250	490	A
Chlorotrifluorovinylidene fluoride	260	50	A
Vinylidene fluoride	270	510	A
Polyethylene (high density)	290	560	A
Tetrafluoroethylene (Teflon)	380	710	A
Methylphenyl silicone resin	>380	>710	B

P-2043

*This is the rating given by Jaffe and Rittenhouse to the probable accuracy of the data where A represents the most trustworthy.

3.7.1.2 Radiation Effects

The threshold value for ionizing radiation damage in polymers ranges from under 10^6 rads to slightly over 10^9 rads with most of the elastomers in the lower part and the glass filled plastics in the higher part. Teflon is the well known exception to the generalizations about effects of structure on radiation resistance.

3.7.1.2.1 Mechanisms of Radiation Damage - It should be noted that the damage is done principally by ionizing radiation, not by displacements. Thus, there can be serious material degradation under prolonged exposure to Van Allen and Starfish Belt radiation. In polymers there are two principal mechanisms of damage, cross linking and scission. In cross linking, the material becomes more brittle; with scission the chains are cut into shorter units and the materials become soft or even liquid in extreme cases. Gases like water vapor, methane, and hydrogen are evolved in copious quantities.

It is possible for cross linking and scission to occur simultaneously or consecutively in a given sample. In some cases the degradation process appears to be catalyzed by oxygen from the air, and results of irradiation in vacuum are substantially better than in air. This is thought to be the reason why the fluorocarbons like Teflon have been used successfully on Telstar in the Van Allen Belt, although they perform very poorly in nuclear reactors and gamma facilities where air is present.

3.7.1.2.2 Criteria of Failure - The criteria of failure of the materials in space vehicles vary. Some properties can be permitted to show as much as a 50 percent change. Gassing, itself, can be tolerated if the gas goes out into space, but not inside a vacuum tube. Because there are so few polymers which come close to space requirements, it becomes important for the designer to determine which shortcomings of a material are unimportant in any particular case.

3.7.1.2.3 Test Results - Bendix has tested polymers for use near nuclear-powered sources and found that polyimides (of which Pyre M.L., H film, and Polymer SP are examples) have radiation resistance comparable or better than radiation hardened electronic circuitry. Some tests on a capro-lactone polyurethane showed mild to moderate damage (softening) at 1.1×10^8 rads of gamma or

X-radiation (tests were performed both in X-ray and gamma facilities) and severe damage (liquefaction) at 1.03×10^9 rads.

DuPont, which manufactures the polyimides, found the threshold damage point for Polymer SP to be 7×10^9 rads (2 Mev Van de Graaf beam). Embrittlement occurred after 1500 hours in the Brookhaven Pile at 175°C, which meant an exposure of about 10^{11} rads, they state. H film remained flexible (180° bend), although slightly darkened, at 5×10^9 Rep at Savannah River. Mylar, a polyester, failed at about 10^5 Rep. The film was also tested at Brookhaven where it was exposed to mixed neutrons and gammas. They state that H film darkened, but did not appear otherwise changed at 8.3×10^{18} n/cm^2. (Flux given as 5×10^2 neutrons/cm^2/sec.) This is a neutron exposure figure. The present authors, in attempting to determine the associated gamma dose, referred to a survey on radiation facilities[72] which indicated that the fast neutron flux of the Brookhaven Pile was never greater than 4×10^{11} n/cm^2/sec, but that there were a number of places where the thermal neutron flux was 5×10^{12}. The gamma flux associated with these places ranged from 1 to 5×10^8 ergs/g (C)/hr. Assuming the lowest value to be applicable, the film received a dose of at least 10^9 rads (1 rad = 100 ergs/g (C)). Except for this gamma dose estimate, all these figures were taken from the manufacturer's literature provided by duPont.

Battelle's Radiation Effects Information Center has published an excellent report on radiation effects on polymers which summarizes in several hundred pages all the data available to about the summer of 1961. Figure 3-10, Relative Radiation Stability of Thermosetting and Thermoplastic Resins, summarizes some of the data. It can be seen that the phenolic glass laminates, which are used as circuit boards, and the polyimides lead the list with Teflon coming in a poor last. The polyimide data is not from reference (73) but from the duPont data mentioned earlier. The data on Teflon in a vacuum comes from a recent paper by Jolley and Reed.[74] The fact that the glass laminates, silica and asbestos filled polymers, are much superior to the unfilled plastic is not entirely surprising. The fillers are used in large amounts, up to 50 percent of the total weight in some cases, and are themselves radiation resistant. They provide an unaffected matrix to hold together the polymer portion.

The electrical or insulation properties of polymers are much less affected by radiation than the physical properties.

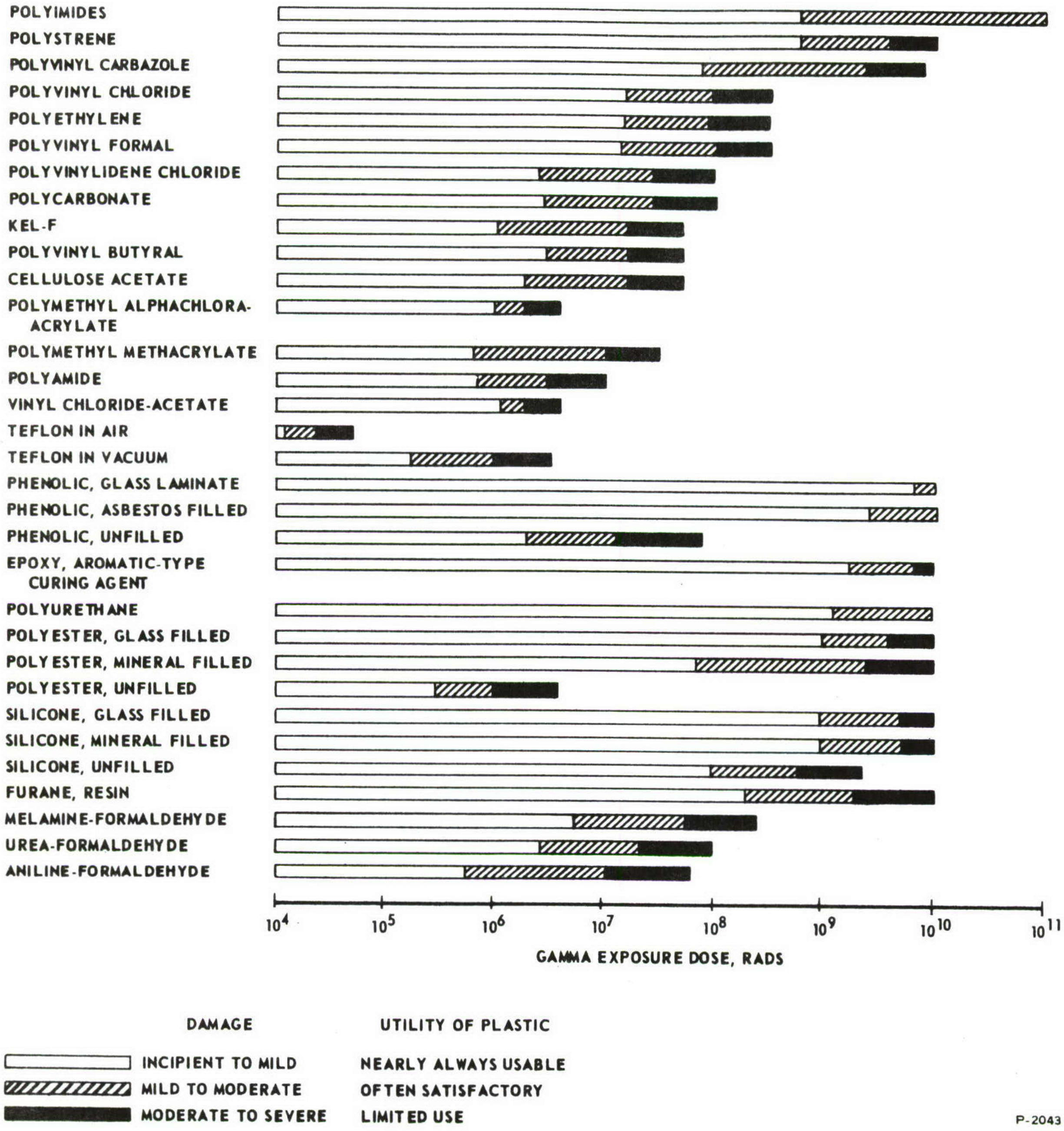


Figure 3-10 - Relative Radiation Stability of Thermosetting and Thermoplastic Resins

As an example of the differences observed by various workers, Figure 3-11[73,75] compares two sets of figures for radiation stability. The set marked REIC came from the summary in the report mentioned previously. The set marked Harrington was published in 1957 and 1958.[75]

It will be noticed that the earlier report is more optimistic than the later. The REIC summary does not appear unduly cautious. Earlier work is difficult to evaluate because accurate dosimetry measurements were not always obtained and there was little previous experience to guide the investigator in setting up tests and describing them as completely as would be desired.

3.7.1.3 Temperature Effects

With most materials discussed to date there was a wide range of temperatures over which they were usable, a matter of 500 to several thousand degrees Centigrade. The polymers are much

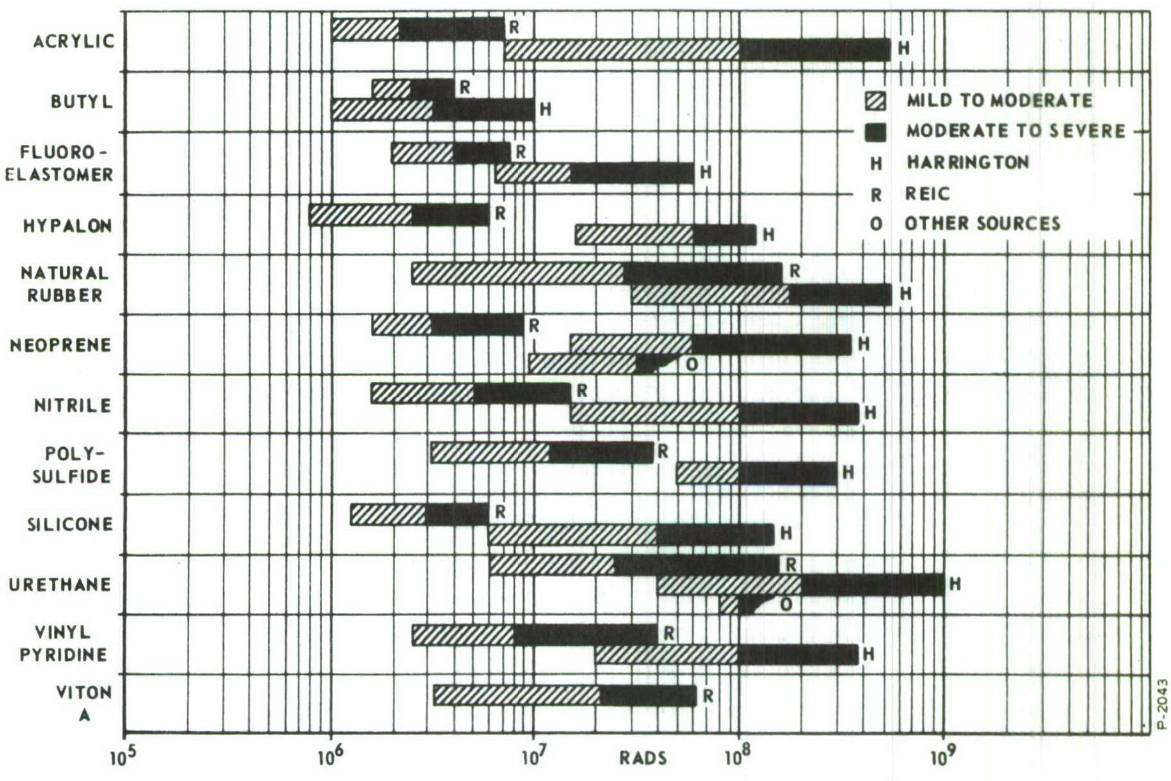


Figure 3-11 - Comparison of Radiation Stability Limits[73,75]

more temperature sensitive. Most get brittle and crack at cryogenic temperatures; they melt or char long before they reach 500°C.

Some of the silicones, some filled phenolics and polyimides, can be used continuously at 275°C; the polyimides at almost 400°C.(76) (They can withstand very short exposures at 500°C.) A typical epoxy-glass laminate suffered reduction of compressive strength and bending modulus at 145 ± 10°C according to Wahl.(56)

The use of polymeric materials as ablation coatings is not being discussed here. This type of sacrificial protection is of interest to nose cone makers, who have been making spectacular headlines by using plastics at fantastic temperatures. Their use of polymer is of questionable value to the electron tube designer who wants his wire insulation to remain in place and function for 10,000 hours.

Fortunately, maximum recommended service temperature data is readily obtainable from handbooks and manufacturers. Thermal-vacuum data is not as available. Table 3-9(4) in subsection 3.7.1.1 shows some of this information, but the wide range of values makes it obvious that there is still room for experimental work.

Behavior at cryogenic temperatures is also poorly documented, except for the fluorocarbons (Teflon, Kel-F, etc.) which are known to be excellent cryogenic materials. Some of the polyurethanes can be used as potting compounds at liquid nitrogen temperatures.(75) The caprolactone type mentioned before was one of the polyurethanes which was tested at Bendix for ability to withstand vibration and shock at such temperatures. It performed well at low temperatures, but this polymer started degrading when the temperature reached +150°C.

Silicones, which are advertised as being useful at low temperatures, are not recommended by the manufacturers for use under -75°F. Unfortunately most manufacturers feel they have adequately investigated low temperature properties when they go down to the -65°F mentioned in so many Air Force Specifications. This data cannot be extrapolated. Elastomers have a brittle point, a temperature at which the material properties change abruptly.

3.7.1.4 Combined Temperature and Radiation Effects

An interesting study of the combined effect of high temperature and radiation on the useful life of insulated wire has been performed by F. J. Campbell of the Naval Research Laboratory.[77]

He worked at air temperatures up to 300°C in a Co-60 radiation field (gamma radiation) and exposed twisted wire configurations to 1.7×10^6 roentgens/hour -- unfortunately Linnenbom does not give total dose. His criteria of failure was the point at which failure occurred when given an electric strength test of 1000 volts. Several materials had increased lifetimes; several had severely shortened lifetimes. Improvements were noted in a polyvinyl formal enamel (increase of 870 percent at 160°C), and a polyester enamel-phenolic varnish (increase of 780 percent at 200°C). Less than normal thermal lifetimes were shown by modified silicone enamel and a poly-tetrafluoroethylene enamel-silicone varnish combination when irradiated.

Smith[78] has described the combination of radiation and low temperature in the NARF reactor facility (fast neutrons, thermal neutrons and gammas). Irradiation of PCTFE (polychlorotrifluorethylene, Kel-F-81) in liquid nitrogen led to a slight drop in tensile strength, but in liquid hydrogen there was a sharp drop in tensile strength as measured immediately after irradiation, while still at low temperature.

Polyimide film and type C polyester film showed an increase in tensile strength as temperature was lowered without radiation. At low dosages, strength increased in liquid nitrogen and decreased in liquid hydrogen; at higher doses the reverse effect was noted. (The exact dosage is not given in the paper, but it appears that low dosage may be in the range of 0.5 to 1×10^7 rads and high dosage 0.5 to 1×10^8 rads.) One possible explanation for these rather odd results lies in the fact than when energy (in this case radiation) is added to organic polymers cross linking and scission may occur simultaneously. The rates of these two opposing reactions depend on so many factors that it would be difficult, if not impossible, to predict which one will predominate under any given condition.

Lockheed-Georgia has also been performing tests under combined nuclear radiation and cryogenic temperature.[79] Burford's brief note indicates that samples were irradiated and tested in liquid nitrogen. (Total dose between 2×10^{14} fast neutrons/cm^2

and 3×10^6 rads and 5×10^{15} fast neutrons/cm^2 and 10^8 rads.) Under these circumstances irradiation did not change physical properties of balsa wood, two polyester polyurethane foams, an epoxy-polyamide and an epoxyamine adhesive, Kel-F, Mylar and H films, aluminized mylar, aluminum-teflon-aluminum laminate, and two phenolic resin impregnated glass cloths. The shear strength of a polyurethane foam went up 39 percent and the tear strength of a fiber glass epoxy laminate decreased.

3.7.1.5 Combined Vacuum and Radiation

Where radiation reaction is predominantly scission (degradation or breaking of bonds), the volatility of a polymeric material will be much greater in a combination of vacuum and radiation than in either environment by itself. Polyethylenes which have been X-irradiated in vacuum outgas profusely, for instance.

At Johns Hopkin's, Frisco et al.,(80) have studied the effects of combined vacuum, X-rays and ultraviolet on electrical properties of dielectrics intended for satellites and space vehicles. Their findings show that (1) electric strengths of low-loss polymers are not affected by irradiation in vacuo, (2) high-frequency breakdown of solids in a vacuum is far more dependent on temperature than on radiation level, (3) d-c properties like surface and volume resistivity are affected by radiation but not by vacuum alone, (4) materials which absorb moisture readily show improved electrical properties after water vapor has escaped in high vacuum, (5) low-frequency loss properties of several fluorocarbons are appreciably affected by radiation. While there is no doubt that the presence of oxygen increases the degradation rate of PTFE (polytetrafluoroethylene, Teflon) with regard to both electrical and physical properties, Frisco's results showed degradation in vacuum as well.

Another combined vacuum radiation test was(77) conducted by Bonnani(81) at the Naval Air Materials Center. Buna N and Neoprene were compared after exposure up to 7.92×10^7 rads in an open atmosphere, in a closed atmosphere (sealed ampoule) and in a vacuum of 5×10^{-5} Torr (sealed ampoule). Buna N showed more severe degradation (loss of over 50 percent of tensile strength and over 80 percent elongation) in a vacuum than in air. Neoprene's tensile strength was not appreciably affected by the same conditions. Although the elongation showed less change in vacuum than in air, there was a substantial decrease in all cases.

Bonnani deduces from these figures that Buna N suffers both scission and cross linking when irradiated in vacuum, while in Neoprene the scission effect is less pronounced. He suggests that his weight gain figures may be the result of carbonyl or epoxy formation in the polymer chain, counterbalanced by formation and outgassing of H_2O, CO, CO_2, and H_2O as the radiation is continued. Bonnani's figures should be taken as tentatively indicative rather than conclusive, inasmuch as his weight changes are close to the accuracy of the balance and his samples were weighed after removal from the extreme environment so they may have resolved various amounts of air.

3.7.1.6 Other Environments

Wahl and his co-workers[56] tested some plastics as well as glass under vacuum-ultraviolet. They found that laminated glass (sheets of glass with thin plastic layers between the glass) degraded at 100 hours of $6 \pm 3 \times 10^{-6}$ Torr and 2 pyrons ultraviolet. This degradation took the form of yellowing and bubbling the plastic layers. Transparent plastics like Plexiglas turned brown under these same test conditions and the light transmittance decreased substantially.

The glass reinforced laminates (polyesters, epoxy, and phenolic) were more affected by ultraviolet and heat, singly or in combination, than by vacuum. The properties measured were compressive strength and bending modulus. Table 3-10[56] gives bending moduli of these laminates under various combinations of test conditions.

The possibility of micrometeoroid damage to wire insulation should be considered if the wires are exposed to open space. Most polymeric material is quite soft compared to the aluminum and stainless steel usually used in micrometeoroid penetration tests. Therefore, a much greater percentage of hits will penetrate rather than bounce off the surface. Some may be caught in the insulation, and if they are non-conductors, may not do much harm, but there will be some that hit with sufficient force to expose bare wire to space, or worse yet, to some metallic part from which it should be insulated. On Surveyor armored wire is being used for external wiring to guard against such damage. This also would protect against ultraviolet radiation and provide some shielding against Van Allen and Starfish radiation belts. In designing vehicles which will spend some months in the radiation belt, the amount and adequacy of this shielding should be calculated carefully.

Table 3-10 - Moduli of Glass Reinforced Laminates While Exposed to Various Environmental Conditions[56]

Test Condition	Bending Moduli x 10^{-6}		
	Polyester	Epoxy	Phenolic
Atmospheric pressure and room temperature	4.67	3.54	4.17
Vacuum pressure ($5 \pm 2 \times 10^{-6}$ torr) at room temperature	4.67	3.54	4.17
Vacuum pressure, UV and moderate temperature (145 ± 10°C)	3.84	2.14	3.94
Atmospheric pressure, UV and moderate temperature	3.38	2.00	3.86
Atmospheric pressure, UV and room temperature	3.75	3.54	3.68
Vacuum pressure and moderate temperature	3.61	2.38	3.96
Atmospheric pressure and moderate temperature	3.75	2.25	3.81

P-2043

3.7.2 Inorganic Dielectrics

The ceramics, which were discussed earlier, are inorganic dielectrics and are used for insulators in the form of sheets, rods, rigid tubes or other cast shapes. Wire insulation and potting and encapsulation of electronic components present different sets of requirements. The wire insulation must have some flexibility in order to maintain its integrity. In encapsulating temperature sensitive devices, obviously the conventional high temperature baking and curing process, necessary for most ceramics, would destroy the device, and therefore cannot be used.

There are now available several kinds of insulated wire which fulfill some of the needs. One, called 1000°F Radiation Resistant Satellite Wire, is claimed by its manufacturer (Boston Insulated Wire and Cable Co.) to withstand radiation doses of 10^8 roentgens (roughly equivalent to 9×10^7 rads) or 10^{19} nvt and temperatures to 1000°F (540°C). Anaconda and Kennecott also market wire with similar properties.

3.8 ENVIRONMENTAL EFFECTS UPON ASSOCIATED ELECTRONICS

Transistors and other semiconductor devices frequently used in power supplies may be damaged by space or reactor radiation in one or more of the following ways: temporary effects due to ionization, surface effects, or crystal lattice damage.

Each of these can be caused by neutrons, gammas, protons, or electrons on the proper radiation energy level and radiation intensity. At the current state of the art of radiation effects in solid state devices it is not possible to write an equivalence between the various radiations

Table 3-11 - Relative Radiation Sensitivity of Electronic Components

	Dose at which there is Significant Permanent Degradation	
Component	Neutrons	Ionizing Radiation (Gamma, X-ray, Proton, Electron)
Transistors	10^{11} to 3×10^{12} nvt	10^4 to 10^7 rads
Diodes	10^{11} to 10^{14}	10^5 to 10^8
Capacitors		10^6 to 10^9

Table 3-11 shows the approximate radiation sensitivity of some electronic components.

It can be seen that a very careful choice of electronic components must be made for vehicles traveling through the Van Allen Belt and those with nuclear power.

3.8.1 Temporary Effects

The temporary effects are ionization dose rate dependent and disappear when the radiation field is removed. The effects are manifested primarily as increases in collector leakage current. For power transistors, increases in I_{CO} of a few microamperes are typical, while for high frequency or switching transistors the leakage in I_{CO} should be in the nanoampere range. Generally, the leakages are not large when compared to normal operating conditions. These temporary effects are of serious significance in the case of nuclear weapons. While they have been observed with steady-state radiation they are of minor significance in such cases.

3.8.2 Crystal Lattice Effects to Transistors and Diodes

Crystal lattice damage is permanent damage dependent on the total radiation dose received by the transistor. This damage is caused by the interaction of energetic radiation with the atoms of the

lattice with resulting decreased minority carrier lifetime and changes in majority carrier concentration. Displacement damage, that is, reduction in minority carrier lifetime, is the primary failure mechanism in minority carrier devices, when surface effects from ionizing radiation do not cause earlier failure.

3.8.3 Surface Damage to Transistors and Diodes

Surface damage, which is thought to be due primarily to ionization rather than displacements, causes permanent degradation. Workers at Bell Telephone[82] have attributed the failure of Telstar transistors to ionization of gases inside the transistor case followed by reaction of these gases with the surface of the active semiconductor element. By evacuating the transistor case, one would then anticipate that the transistor would be less susceptible to this type of damage and would probably operate for a longer period of time. This has been shown in Telstar II where evacuated transistors were used in place of dry-air filled units in Telstar I. A comparison of performance of the transistors in these two satellites is shown in Figure 3-12.[82]

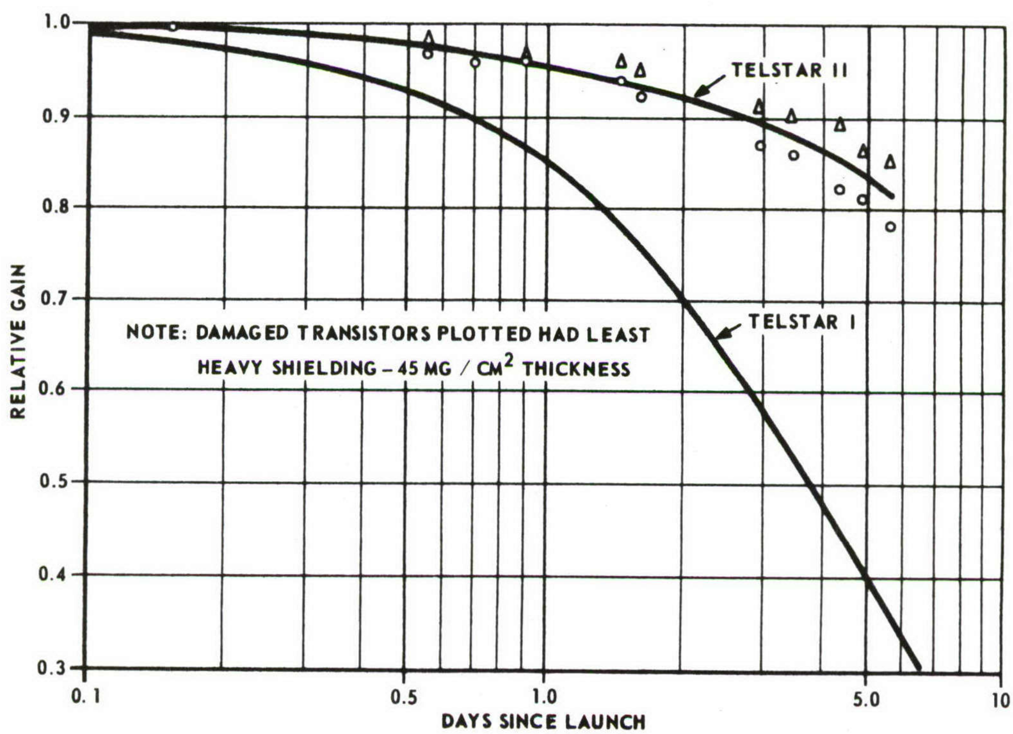


Figure 3-12 - Radiation Damage to Transistors in Telstar I and II[82]

Workers at other institutions, including Bendix, are also performing studies which will lead to a better understanding of damage mechanism. An indication of the extent and seriousness of these property changes is shown in a recent paper by Rogers[83] where he shows that after exposure to 10^4 rads, the observed grounded emitter current gains for silicon mesa transistors were from 0.1 to 3.0 of the initial gain with many units in the 0.5 to 0.8 range (20 to 50 percent decrease in gain). Exposure of silicon planar transistors to 10^5 rads has been shown to reduce gain to a figure as low as 0.4 of the initial gain, although many units were in the 0.6 to 0.8 range. He points out that the same dosage caused no significant change in properties of carefully processed mesa transistors in evacuated cases.

Since transistors and diodes are hermetically sealed, those in metal cases are unlikely to be damaged by vacuum.

3.8.4 Capacitors and Resistors

Those capacitors which do not contain liquid electrolytes or organic materials are equally vacuum-resistant and more radiation resistant than transistors. Resistors are generally even less sensitive to these environments.

Experience at Bendix has shown the need for careful examination of the packaging and sealing techniques used before specifying electronic components. The manufacturers' literature seldom includes results on environmental tests.

SECTION 4

DESIGNING SPACE-ORIENTED TUBES

4.1 GENERAL CONSIDERATIONS

It was pointed out in the introduction that space-oriented tubes must possess the features of high reliability, high efficiency, and low mass. Doubtless other specifications would be applied depending on the mission. For example, there might well be a restriction on the harmonic output power or intermodulation products in the case of a communications app ication.

There is, of course, a great deal of interrelation among the desired characteristics above. It is obvious that high efficiency brings with it a mass reduction in the over-all package including the power supply. Furthermore, it reduces the prime power demand and simplifies the problem of dissipating any unused input power as heat.

It is of interest to discuss these factors individually and then to propose a general design approach.

4.2 DESIGNING FOR HIGH RELIABILITY

4.2.1 Results of the Materials Study

The environmental survey and materials study furnish the factual information necessary to choose with confidence the materials that should be used in designing and constructing a power amplifier tube for use in a space environment. Some of these materials are currently being used in tube fabrication but under certain environmental and operating conditions further restrictions are necessary. The following recommendations are made:

(1) Ceramic-metal construction of the tube. Glass can be used but requires adequate packaging

(2) Shielding of the power supply semiconductor components in 1 gram/cm^2 aluminum shell or equivalent

(3) Use of inorganic type potting compounds and wire insulation

(4) Use of high temperature seals

(5) Permanent magnet materials in general. The Alnico materials seem to survive the combined environmental stresses best. Platinum-cobalt is recommended when weight savings are paramount. There will be a radiation hazard whenever the cobalt alloys are exposed to neutron bombardment such as in a nuclear-reactor environment. Magnetic properties in general are more apt to be impaired by high temperatures than by radiation.

4.2.2 Cathode Protection

The tube designer is well aware of the cathode's role as a tube life determiner. In a space application, the long life requirement makes cathode design especially critical. It is therefore important to include the following precautions:

(1) Design the heater-cathode assembly to be as thermally efficient as possible so that it will operate with minimum heater power and at low heater temperature.

(2) Use a very conservative cathode loading (amps per square centimeter). As a comparison, if one classifies 1 amp/cm^2 and 5 amps/cm^2 for oxide and dispenser cathodes, respectively, as being typical of hundreds of hours operation, (non-orbital missions), then the space-tube application should utilize loadings of less than 100 ma/cm^2 and 500 ma/cm^2 to insure very long life. Telstar I used a TWA with an oxide cathode whose loading was approximately 80 ma/cm^2.

(3) Pay special attention to the condition of vacuum within the tube in all phases of its life. A rigorous processing regime should be adhered to at manufacture. During storage and rise-to-orbit the tube must be completely vacuum tight.

Once in space, one might consider opening the tube envelope presumably to the hard vacuum of space. This can be done only if two conditions can be assured. The first and obvious condition is that the tube will not be exposed to a denser atmosphere at any time after

opening the envelope. This is very important if the tube's mission takes it into a planetary atmosphere, say a Venus or Mars probe, or if re-entry to earth is planned. The second condition is the assurance that the tube's own immediate environment, even in space, is free from contaminants such as might be present due to outgassing of adjacent components. This is more often the case than not and the tube may very well never, in its useful life, be exposed to the true space vacuum.

(4) Use ion traps to protect the cathode. Such traps could be easily realized without interfering with the beam optics by including in the gun design an Einzel lens whose center electrode runs at lower potential than the outer electrodes and hence attracts positive ions.

A magnetron-injection type gun is inherently less susceptible to ion bombardment even without ion traps.

Finally an electrostatically-focused tube will drain ions along its entire length and therefore will tend to protect the cathode. This type of focusing should be considered if it satisfies other requirements.

4.2.3 Heat Dissipation

The tube in space resides in a thermally isolated environment and hence in the final analysis any heat developed by the tube must be radiated away from the satellite.

In the power ranges discussed in this study, e.g., 100 watts at X-band and 10,000 watts at 1 Gc, the heat developed will be considerable even if all means are taken to improve efficiency as discussed in subsection 4.3. The problem is really twofold, the first being to move the heat out away from thermally fragile interaction structures and secondly to carry this heat plus that generated on the beam collector to a final radiator of adequate capacity. Let us consider this latter, or major problem first.

The importance that high efficiency performance in a space tube plays in this one problem, heat dissipation, is evident in Figure 4-1. Here is plotted the radiator area necessary to radiate the unconverted

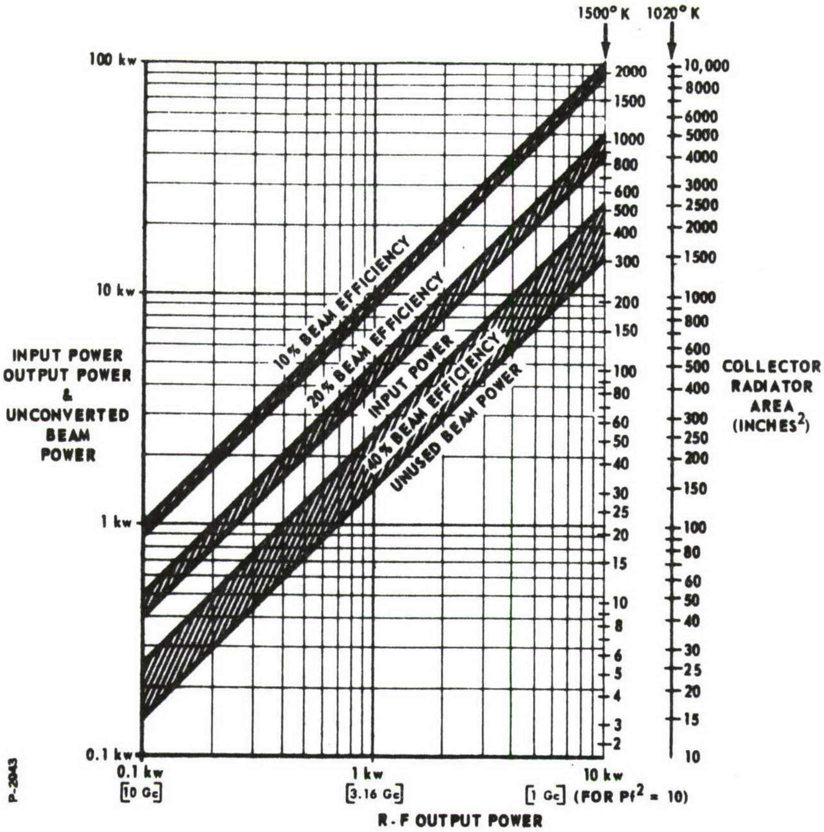


Figure 4-1 - Radiator Area Versus Power
(Assuming Radiator Emissivity = 0.25)

input power of a tube for various power levels and beam efficiencies. The designer can enter the graph at the abscissa point corresponding to the desired power output and move up vertically to the set of lines corresponding to the beam efficiency expected. The top line of each efficiency set gives the input power, the vertical distance between lines represents the r-f power output, and the bottom line indicates the unconverted power to be dissipated. Moving from the bottom line horizontally across to the ordinate scale on the right, one finds the area of radiator required for two specified radiator temperatures, assuming an emissivity of 0.25. This assumes radiation into a near-absolute-zero-temperature sink.

The conclusion is that the surface area of radiator required for the higher power tubes is very large unless the radiator temperature is extremely high. This suggests that the radiators for space tubes

might well be made of the refractory metals. In the case of a traveling-wave amplifier, for example, the collector might be made of molybdenum or tungsten and could be finned to serve as the radiator. This design approach emphasizes the upcoming importance of very-high-temperature ceramic-metal seals -- a metallurgical problem now under study.

4.2.4 Heat Energy Reclamation

The above discussion also points up the desirability of either reclaiming the unused beam energy before it is converted into heat, i.e., the depressed-potential collection techniques described in subsection 4.3.3; or using some type of thermal-to-electric converter.

The direct-heat-to-electric converters have been considered for this purpose from time to time. However, in general it would seem that unless the conversion efficiency of such devices is improved considerably above the present state-of-the-art values, it would not help the over-all situation. The added complexity and weight of such attachments would probably balance out the advantage gained in electrical energy recovery.

In turbonuclear powered vehicles, it should be desirable to couple the waste heat of a microwave power tube back directly into the turbine cycle through a heat exchanger.

It seems logical, however, that a tube designer's time could best be spent in increasing the basic conversion efficiency of the tube, and then in reducing all other power losses by careful attention to design detail and recovery schemes.

4.3 DESIGNING FOR HIGH EFFICIENCY

4.3.1 Introduction

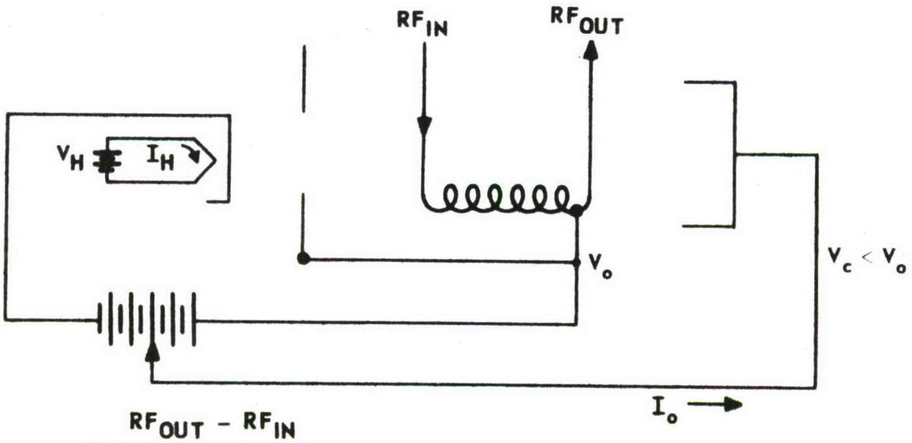
There are three efficiencies of importance in any discussion of microwave tubes -- the conversion efficiency, the beam or plate-circuit efficiency, and the over-all efficiency. The first of these, the conversion efficiency, is defined as the ratio of the r-f power developed by the tube (r-f power output minus r-f drive power) divided by the beam power in the interaction region. This efficiency is a measure of the ability of the tube to convert d-c into useful r-f power. It is very important to obtain a conversion efficiency as high as possible for this gives a large r-f output power and leaves much less unused, potentially wasted beam power.

The beam efficiency is defined as the r-f power developed in the tube divided by the actual d-c beam power supplied by the power supply, a power that is not necessarily the same as the beam power in the interaction region. As a point of fact, the plate efficiency can often be higher than the conversion efficiency, if techniques are employed to decelerate the electron beam after it has passed through the interaction space but prior to its collection -- the aforementioned depressed-potential-collection schemes.

Finally, the over-all efficiency takes into account the additional heater power and focusing power when used and therefore is defined as the r-f power developed by the tube divided by the sum of the beam power and the heater power and focusing power. In summary, refer to Figure 4-2 for a traveling-wave amplifier example.

4.3.2 Conversion Efficiency

The most fundamental of all the efficiencies, of course, is the conversion efficiency. If this can be made high, then there is little need to employ sophisticated schemes later for improving the



$$\eta_{CONV} = \frac{RF_{OUT} - RF_{IN}}{I_o V_o}$$

$$\eta_{BEAM} = \frac{RF_{OUT} - RF_{IN}}{I_o V_c}$$

$$\eta_{OVER\text{-}ALL} = \frac{RF_{OUT} - RF_{IN}}{I_o V_c + I_H V_H + P_{FOCUSING}}$$

P-2043

Figure 4-2 - Schematic Diagram of a TWA Defining the Various Efficiencies of Interest in Microwave Tubes

beam efficiency. In general, however, wide band power tubes of the linear beam type such as the traveling-wave amplifier are characterized by only moderate conversion efficiencies (15-30 percent) unless special designs are exploited. The narrow band tubes such as the klystron do possess higher conversion efficiencies. Also the crossed-field amplifiers and the amplitron which exhibit medium bandwidth, have higher efficiencies, but in this case, the energy exchange mechanism is different, being a transferral of potential energy to r-f rather than a conversion of kinetic energy to r-f power.

4.3.2.1 Phase Focusing

In all microwave electron-beam tubes, the energy is extracted from the power source through the mechanism of beam bunching. Viewed from a particle dynamics point of view it is necessary to form the electrons into bunches and to maintain the center of gravity of the bunches in the decelerating field of the r-f to be amplified. With crossed-field devices the balance or focus is fairly easily maintained since the bunches move essentially in synchronism with the traveling r-f field in the longitudinal or cathode-to-collector direction but move transversely through a drop in d-c potential as they give up energy to the r-f wave. With linear-beam tubes of the traveling-wave type, there is an inherent difficulty in maintaining the electron bunches phase-focused in the decelerating field of the traveling r-f wave since the only source of energy is the kinetic energy that the electrons received prior to entering the r-f interaction space. Hence, the bunches tend to fall back out of step with the r-f wave as they give up energy to it.

Klystrons suffer from the same type of phase focusing difficulty but not in quite the same way or as severely. Since the transfer of beam energy to r-f takes place at a discrete space position (the output cavity gap) there is no slipping behind the wave in the traveling-wave tube sense. However, the problem of transit time comes into play if large amounts of power are extracted from the beam. Under this condition, the beam slows down so much that the transit time across the output gap becomes an appreciable fraction of an r-f cycle, resulting in an inefficient interaction. Space charge tends to build up in the gap too, adding further complication.

4.3.2.2 Techniques for Maintaining Phase Focusing

The traveling-wave tube has many desirable characteristics for space use, particularly its broad bandwidth when using a helix-type circuit. However, as pointed out, the traveling-wave amplifier's conversion efficiency is limited by the tendency of the electron bunches to slip out of phase when large amounts of power are extracted. In order to diminish the efficiency degradation due to this cause, steps must be taken to keep the electron bunches in step with the r-f wave as long as possible during their transit through the interaction space. This can be done in two ways: One can reimburse the electron bunches with d-c power while they are in the process of giving up power to the r-f, such as would be accomplished through the use of an accelerating d-c gradient in the interaction region; or the r-f wave can be slowed in a tailored fashion so that the bunches remain phase focused with the r-f wave as they give up energy to it, corresponding to the tapered phase velocity approach.

The helix-type traveling-wave amplifier does not lend itself very well to the d-c gradient technique but can be constructed to have a tapered phase velocity by simply varying the helix pitch in a prescribed manner. The pitch profile versus length must be chosen quite carefully, however, and this requires a beforehand knowledge of tube parameters; e.g., voltage, current and operating conditions such as drive level. Given these condtions the pitch profile can be arrived at through the use of large-signal analysis of the TWA or even by suitable approximate design criteria.(84) Laboratory experiments have shown that conversion efficiency improvement of about 3 db is possible using this technique.(85) This means that conversion efficiencies of over 50 percent are feasible.

4.3.3 Beam Efficiency: Depressed - Potential Collection

Viewed from a power supply point of view, the beam efficiency is simply the ratio of the r-f power developed by the tube divided by the d-c power input to the beam, excluding heater power, etc. Beam efficiency can be made high even though the basic conversion efficiency remains low. By manipulating the beam leaving the interaction region in such a way as to slow it down, collection is accomplished with a minimum dissipation of energy as heat. Again it must be noted that this technique does not lead to increased r-f power out.

The technique most used to improve the beam efficiency is the depressed-potential collector. Basically, it satisfies two requirements -- it sorts the beam leaving the interaction region into several velocity classes and then collects each velocity class on a collector segment whose potential has been chosen to decelerate the electrons striking it to as low a residual velocity as possible without complication in the form of space charge buildup or turning back of electrons.

The operation of a traveling-wave amplifier from a power point of view is descriptively shown in Figure 4-3. Tubes having low conversion efficiencies almost always have the least velocity spread in the beam when it leaves the interaction space. Therefore, much of the remaining beam energy can be reclaimed by using a depressed-potential collector of only one or two segments. On the other hand, any tube operating at high conversion efficiency will have a large velocity spread in the beam and is a poorer candidate for depressed-potential collection unless several segments are used. Depending on the conversion efficiency of the tube, the energy spread in Figure 4-3 will assume the relative curvature of one of the plots shown at the bottom of the figure.

4.3.4 Summary on Efficiency

There seems to be no question that from an efficiency point of view the main goal in a space tube should be to raise the conversion efficiency in order to enhance the r-f output and to minimize the losses.

Further reduction of prime power and heat dissipation can be achieved through use of depressed-potential collection, but the added complication of additional power supplies and added focusing weight must be taken into account. It would seem that single or two-stage depressed collection would be the limit unless certain special forms of this approach can be exploited in a particular satellite application. One of these special forms is discussed in a subsequent section.

4.4 DESIGNING FOR MASS REDUCTION

4.4.1 Factors Affecting the Weight of a Tube

In space tubes it is always necessary to design the entire electronic package for minimum total mass although there may be tradeoffs to consider between various tube parts and the power supply.

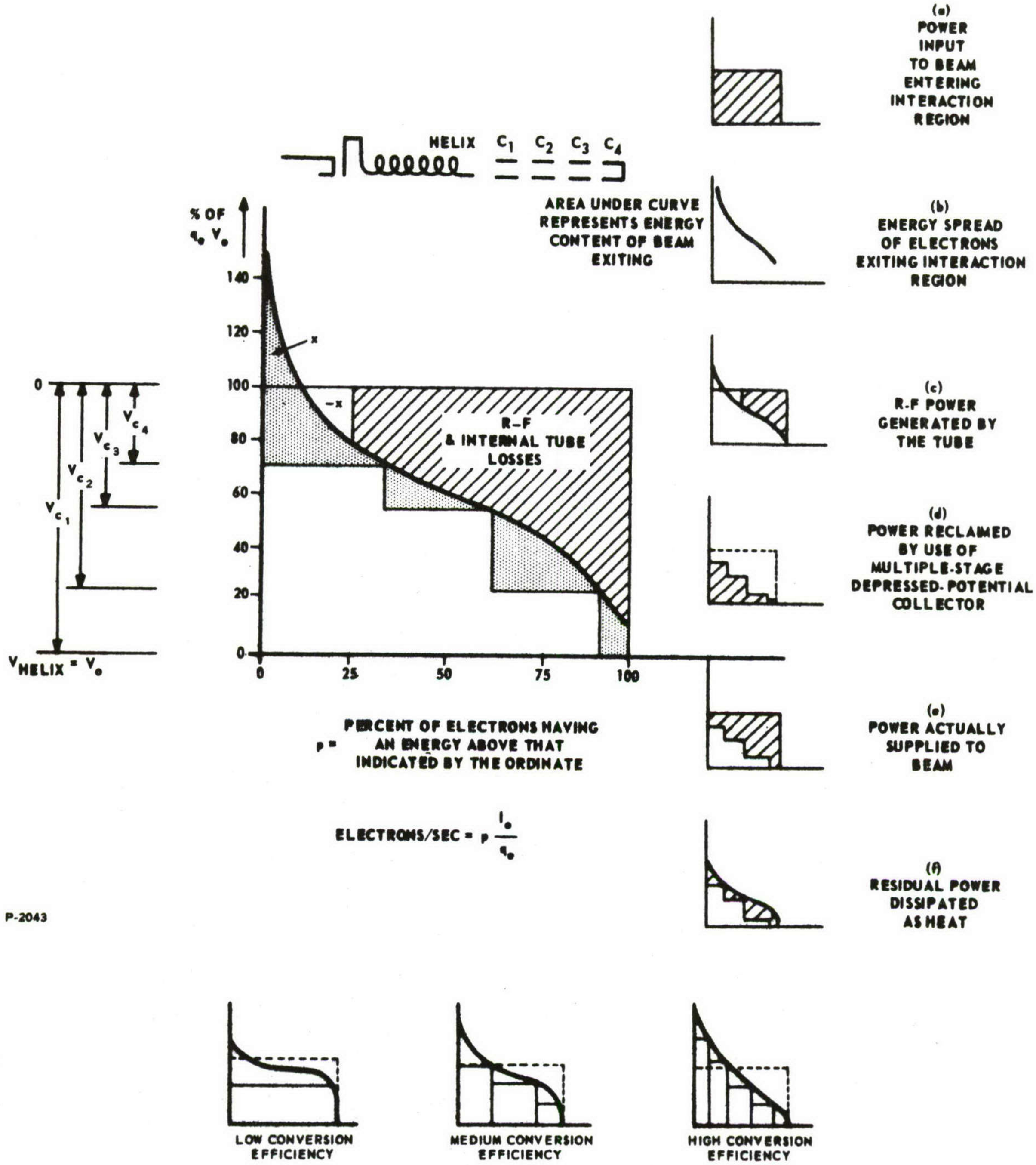


Figure 4-3 - Power Division in a Traveling-Wave Amplifier with 4-Stage Depressed Collector

Essentially, a linear-beam tube, such as a traveling-wave tube, consists of four major parts: an electron gun, a beam collector, an intervening slow-wave circuit, and an encapsulating focusing structure. All of these elements scale with the power level of the tube but there are optimum choices for the electrical parameters at any given power.

4.4.1.1 Idealized Analysis of a Minimum Weight Solenoid Focusing Structure

Of the component parts of a tube the focusing structure is perhaps the chief contributor to the weight of the tube package. In this section the tube operating conditions that lead to minimum weight focusing are analyzed and then in subsection 4.6 the practical problems that prevent achieving this minimum in many instances are pointed out.

It is instructive to see how the weight of that classical focusing structure, the solenoid, varies with frequency, power, voltage, etc., and how these choices should be optimized to minimize the weight. The operating conditions that lead to minimum solenoid weight should also apply to the more sophisticated focusing methods such as PPM (periodic permanent magnet) focusing.

The analysis is based on the assumption that the weight of a solenoid is proportional to the volume and then it defines the volume as a function of frequency, beam voltage, current, etc. A further design choice must be made; whether the solenoid is energized at constant current density in which case the power input among solenoids varies, or whether the power input is kept constant in which case the power density among solenoids varies. Results based upon both assumptions are presented. For the solenoid shown in Figure 4-4, the following proportionalities apply:

(1) Weight $\propto a \Delta L$

(2) $\Delta \propto n$ times the diameter of the wire where n is the number of layers of wire.

(3) Diameter of the wire $\propto a$, if constant solenoid power is assumed; it is independent of core diameter if constant current density is assumed.

(4) $B \propto n$

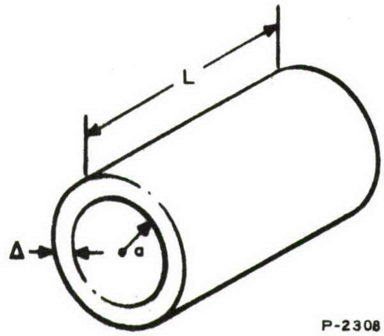


Figure 4-4 - Solenoid Geometry

(5) $Ba \propto (Perv)^{1/2} V_o^{1/2}$ from the Brillouin focusing criterion for solid beams.

(6) $fa \propto (V_o)^{1/2}$, from the assumption that γa is a constant for all TWA's.

(7) $L \propto V_o^{5/6}/f\, I_o^{1/3}$, assuming that the gain, BCN, is constant.

Combining these relationships,

$$\text{Weight} \propto (I_o V_o)^{1/6} V_o^{11/12}/f^2$$

for constant solenoid power

or

$$\text{Weight} \propto (I_o V_o)^{1/6} V_o^{5/12}/f$$

for constant solenoid current density

where

I_o = beam current

V_o = beam voltage

and f = the TWA operating frequency.

The conclusion drawn from either of these expressions is that the weight of a focusing structure is minimized by using as low a beam voltage as possible for any power and frequency. As will be seen in subsection 4.6.1 there are important limitations on beams and circuits which prevent solid-beam operation at very low

voltages. By the same token the use of hollow beams does enable one to utilize reasonably low-voltage operation at the low frequency end of the spectrum with the result that these tubes are considerably shorter than they would be if only solid beams were available. At higher frequencies solid beams and higher voltages are both necessary (as will be explained in subsection 4.6.1.3) and tolerable because the higher frequencies bring about a reduction of dimensions.

4.4.1.2 Power Supply

The power supply requirements for space vehicles will vary according to the purpose and mission to be performed. For this discussion, however, the power supply for auxiliary and electronic payloads will include only the microwave power amplifier. The driver or general purpose tube power requirements will generally be of the low power types and will not add significantly to the power supply requirements. The power supply for the power amplifier and as many other requirements as feasible should be designed in conjunction with these devices so that the minimum size and weight and maximum efficiency can be achieved. Thus, space and electrical utilization to achieve an optimum design for the vehicle can be attained when all of the requirements are simultaneously considered in the design stage.

The prime power available will be dictated by the magnitude of the power required and time duration of the mission to be accomplished, as shown in Figure 1-4. The type of prime power will to a large extent influence the microwave devices and associated power supply designs. For example, if a nuclear prime supply is used, a type of cooling will be available for tube use but shielding the tube or power supply will require additional considerations. The input power requirements as a function of frequency are shown in Figure 4-5.[86]

To illustrate the region in which the prime power requirements fall, the information on power amplifier tubes shown in Figure 4-6(a) will be used. Thus, referring to Figure 1-4, the type of prime power for a mission duration exceeding one week will be solar mirrors or nuclear fission. If additional electronic payloads are aboard, undoubtedly a nuclear fission prime power source will be required.

The efficiency of the power supply for the power amplifier tube and driver tubes can be between 80 and 90 percent. Assuming the power supply will be integrated for both tube functions,

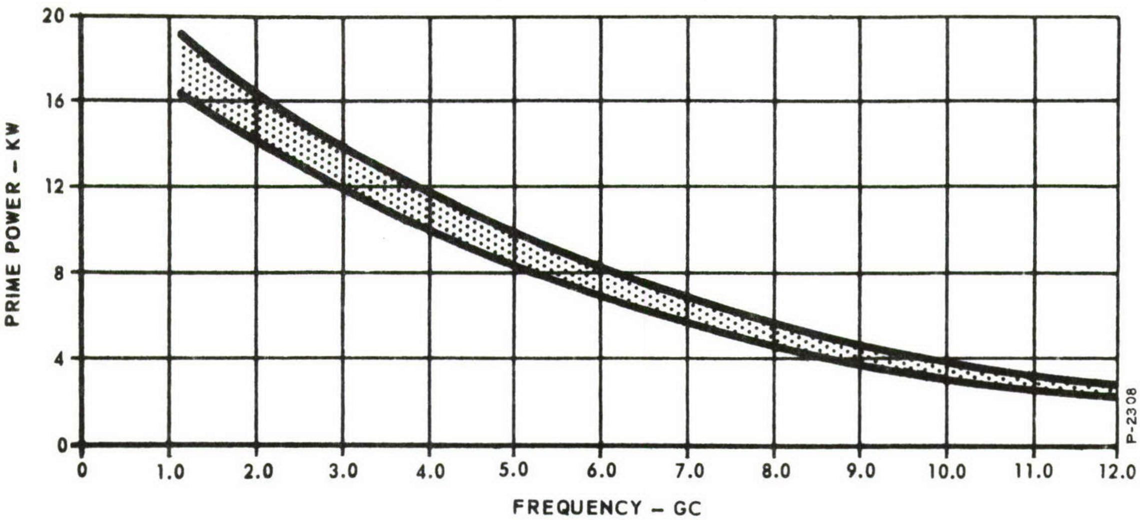


Figure 4-5 - Prime Power Requirements for Anticipated Power Amplifier Tubes for the Late 1960's[86]

an over-all design may appear as shown in Figure 4-7. Essentially, the driver tube is supplied at little expense in terms of power, additional size, and additional weight. Through the use of advanced components, a typical power supply would be as shown in Figure 4-8. The weight of this type of supply would be about 30 pounds for operating a 1-kw tube and driver. Thus, it can be seen that one can no longer assemble state of the art components to provide an electronic function for space missions but must design each device into the system taking full advantage and optimizing all compromises to realize the ultimate in performance, size, and weight.

4.5 PROJECTED STATE-OF-THE-ART FOR LINEAR-BEAM TUBES IN THE LATE 1960'S

The previous sections have been concerned with some of the general areas currently receiving attention in attempts to improve the performance of linear-beam tubes, particularly traveling-wave tubes. Although it is always risky to look ahead it is interesting to try to project the state-of-the-art for the late 1960's in the light of present knowledge of current research trends.

Figures 4-6(a) and 4-6(b)[86] plot such an attempt. On this graph the over-all efficiencies, CW power outputs, and weights that may be expected in the next two or three years are plotted versus frequency.

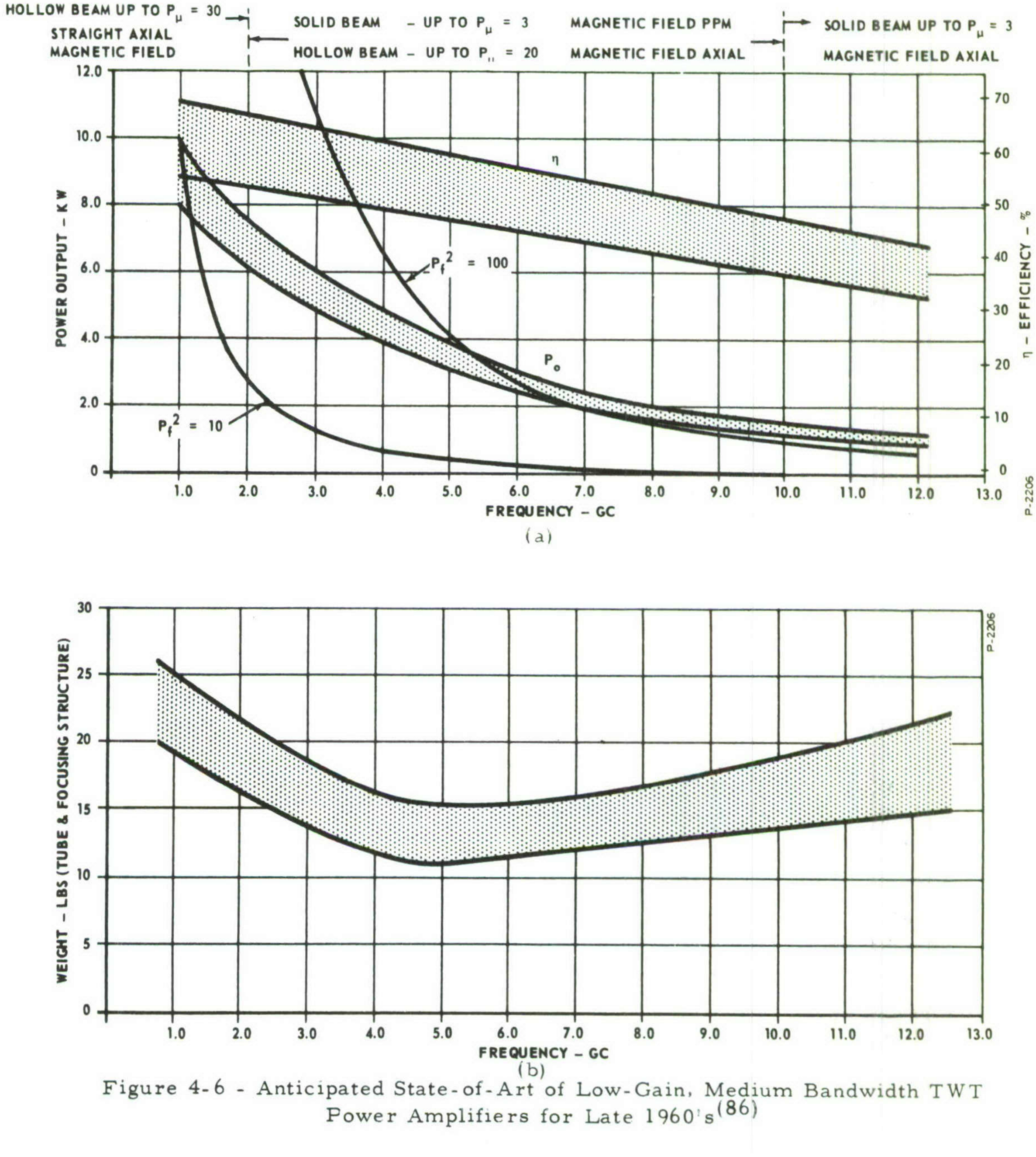


Figure 4-6 - Anticipated State-of-Art of Low-Gain, Medium Bandwidth TWT Power Amplifiers for Late 1960's[86]

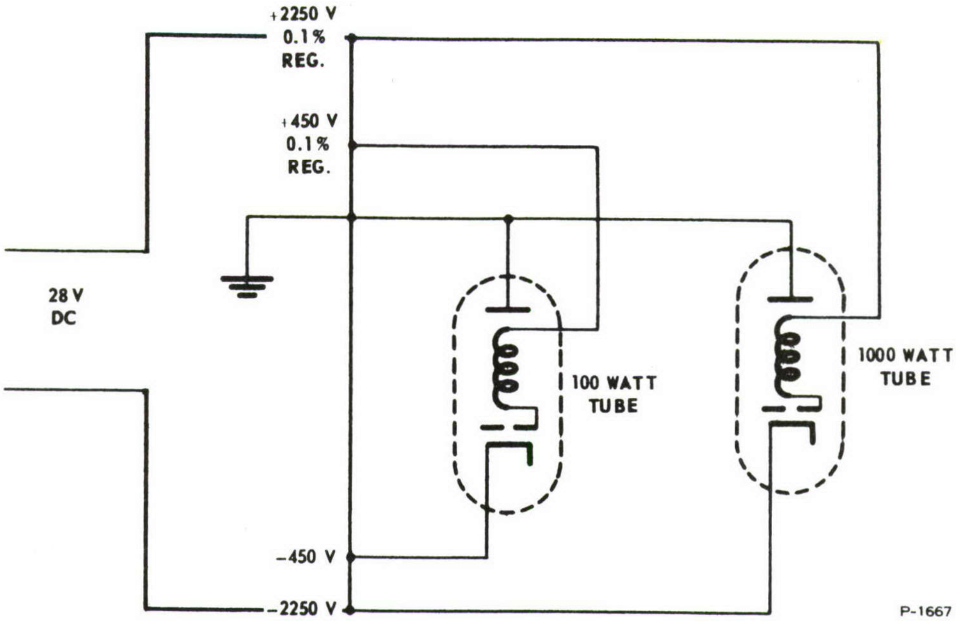


Figure 4-7 - Driver and Power Amplifier Tube Power Supply Schematic

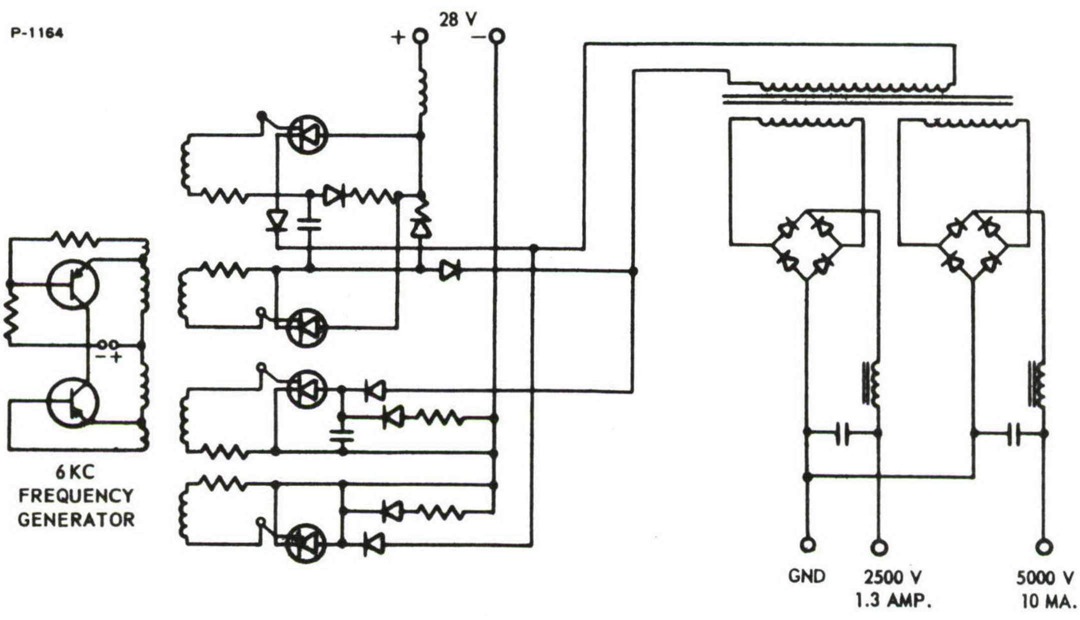


Figure 4-8 - DC-to-DC Converter Power Supply

The tubes depicted are considered to be of either the narrow-band, medium-gain variety or medium-bandwidth, low-gain type.

4.6 PROBLEM AREAS FOR SPACE-TUBE DESIGNS

The basic problems in microwave linear-beam tube design fall into certain well-defined categories. These problems are associated with

(1) The formation and focusing of the high-perveance beams generally required for power tubes.

(2) The selection of the circuit based upon electrical objectives, mechanical support, and heat handling capability.

(3) The design of the collector to improve plate circuit efficiency and to minimize heat dissipation.

4.6.1 Difficulties in Beam Formation and Focusing

The problem in high-perveance gun design is to draw a beam uniformly from the cathode and to propel it with minimum interception through the anode aperture. The perveances that can be reasonably generated by solid-beam guns are limited to 3 or 4 x 10^{-6} amp/(volt)$^{3/2}$. With hollow-beam guns the perveances achievable are considerably higher: 10, 20, and even 30 x 10^{-6} not being uncommon. However, for hollow-beam guns the perveance-per-square is of more significance than perveance. Perveance-per-square is a number obtained by dividing the perveance by the number of squares of dimension equal to the beam thickness that can be scaled around the beam circumference. The limiting value for perveance-per-square is of the order of 0.25 to perhaps as high as 1 x 10^{-6}. Beyond this value of perveance-per-square hollow-beams are apt to break up.

High-perveance electron beams have been studied extensively regarding cathode current density limitations, velocity spread and potential depression of the beam from the circuit.

4.6.1.1 Cathode Current Density Limitations

As was pointed out in subsection 4.2.2, the reliability requirement forces the use of rather conservative cathode current densities to insure the long life of the cathode. Densities less

than 100 ma/cm^2 for oxide cathodes and less than 500 ma/cm^2 for dispenser type cathodes seem advisable. This means that converging beam guns must be utilized for high-power tubes in order to furnish the required currents. Gun designers have found that the product of area convergence ratio times microperveance is limited to 100 or so for solid beams. Hollow-beam area convergence is most easily accomplished through the use of magnetron injection design with perhaps additional magnetic convergence. The area convergence times microperveance achievable in this way is about 200-300.

There is a definite relationship between the beam current density required at any power level and the upper frequency of operation. This again is because the circuit cross section scales with the operating wavelength for proper traveling-wave interaction. For a solid electron beam Eastman(87) relates these factors to a reasonably accurate approximation by the expression

$$R\,J_c = 0.112\,P^{1/5}\,(P_\mu)^{4/5}\,f^2$$

where

$R\,J_c$ = the product of cathode current density and area convergence ratio, i.e., the beam current density

P = the beam power in kilowatts

P_μ = the microperveance

and

f = the upper frequency limit in Gc.

Here one can see how important it is to obtain high density beams as the frequency moves up into the millimeter regions.

4.6.1.2 Velocity Spread in Beams

Velocity spread within the beam is not generally a condition favorable to the operation of traveling-wave amplifiers. It is usually desirable to hold the velocity spread to less than 5 percent; a value reached at a perveance of 6.25×10^{-6} for solid beams and at a perveance of 30×10^{-6} for hollow-beams of thickness equal to one-fifth the radius.(88) This limitation on perveance occurs at about the same values as are imposed in practice by the beam-forming problem discussed above.

4.6.1.3 Potential Depression of the Beam from the Circuit

When high perveance beams are passed along within a metal cylinder (the slow-wave circuit) the negative charge causes a depression of potential so that the electrons move with a velocity considerably below that associated with the cylinder's potential. This effect is in addition to the velocity spread within the beam discussed in the previous paragraph and should be kept low for good performance. The potential of the outer edge electrons can be brought nearer to that of the circuit by locating the beam physically closer to the metal cylinder. Figure 4-9 shows the relationship between the normalized space-charge depression of the beam potential (in percent) and the beam microperveance with the ratio of cylinder radius to the

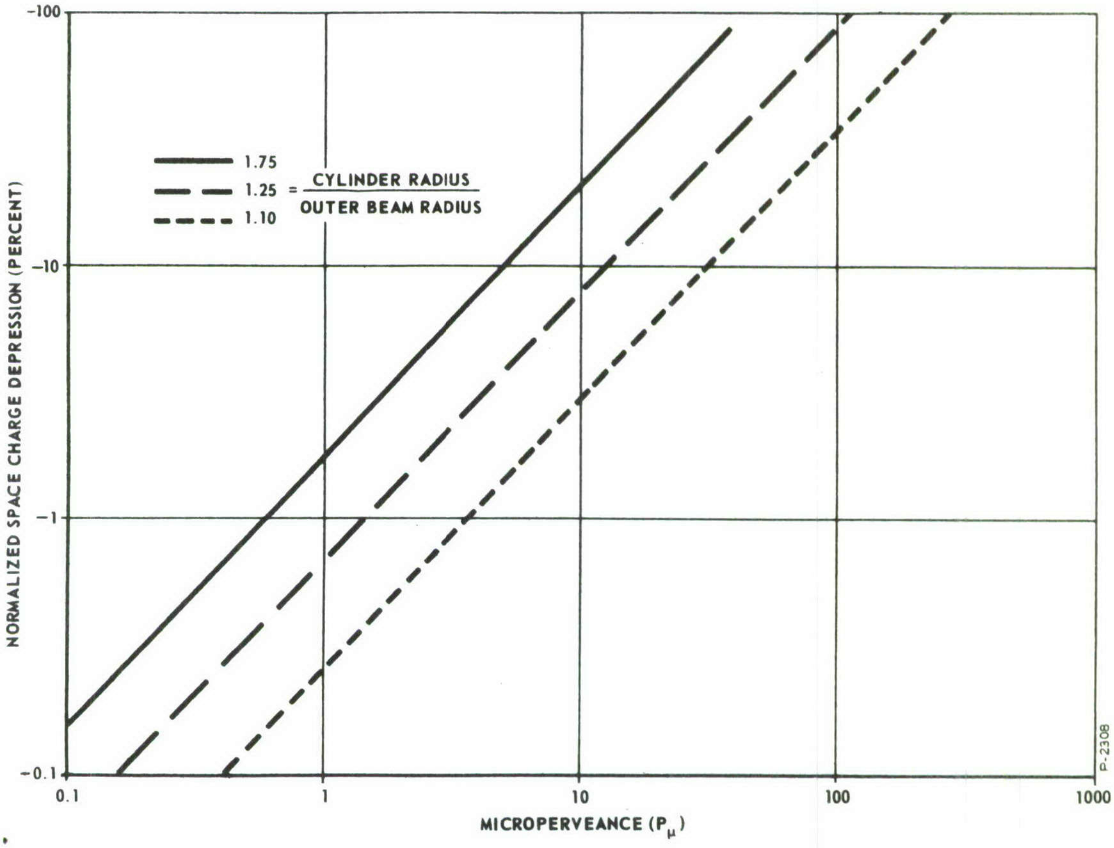


Figure 4-9 - Percent Space-Charge Depression of Potential of Outer Beam Electrons from Potential of Surrounding Metallic Cylinder

outer beam radius as a parameter. As pointed out by Eastman[87] values of microperveance of 30 or so require spacings within 10 percent of the cirucit wall in order to prevent excessive potential depression, e.g., over 10 percent. This places a most severe requirement on the focusing to prevent beam interception on the circuit especially near the output end of the tube where beam bunching is present.

This condition is a further restriction on the use of high perveance hollow-beams at the higher frequencies where the 10 percent spacing from the circuit translates into a very small absolute spacing. By the same token the restriction is not so binding in lower frequency tubes.

4.6.1.4 Restriction on Operating Voltage

While it would be advantageous to work with slow velocity beams it has been shown that there are several difficulties which set lower boundaries on voltage for any beam power. Expressed in terms of perveance it can be stated that solid beam perveances up to only 3 or 4 x 10^{-6} $\left[amp/(volt)^{3/2}\right]$ can be controlled while perveances up to 30 x 10^{-6} or so are useable with hollow-beams if the perveance-per-square value does not exceed 0.25 x 10^{-6} to perhaps 1 x 10^{-6}. These values dictate a voltage above which one must operate. This minimum voltage can be determined for any application once the beam power and the type of beam are specified. The limiting voltage is

$$V_{min} = 3.98 \, (P/P_{\mu})^{2/5}$$

where

P = beam power in kilowatts

P = microperveance

and

V_{min} = minimum voltage in kilovolts.

4.6.2 Limitations of Slow-Wave Structures

The slow-wave structure used in a traveling-wave tube power amplifier should possess the qualities of high interaction impedance, power and bandwidth capacity adequate to the application, and required mechanical strength. For space duty, moreover, the structure should have excellent thermal stability, that is, it should

accept and transfer incident heat without deterioration over long life. In the interest of high efficiency, it would also be desirable to have a structure which lent itself to the "tapering" of its electrical characteristics to enhance phase focusing. Finally, light weight would be promoted if the circuit was amenable to enlightened schemes for electrostatic focusing of the electron beam.

Obviously no one circuit is best in all the above attributes and in that sense all circuits have limitations. The characteristics of the common type circuits are discussed below.

4.6.2.1 Helix-Type Structures

The helix circuit is in many ways synonymous with traveling-wave tubes. It possesses very broad band capability and can be electrically tapered by simply varying the pitch to follow a prescribed profile. In the past the most serious disadvantage of helices has been their rather low average power capacity, especially at high frequencies where the small wire size makes it thermally fragile. Recently though a great deal of effort has been devoted to experiments utilizing beryllium oxide to support the helix within its metal shell. With proper attention given to obtaining a good pressure contact between helix and support rods and between rods and shell the excellent thermal conduction of this material raises the helix power handling capability considerably. Figure 4-10 shows the achievable power versus frequency for helix-type tubes from work by Detweiler.[89]

Besides the simple helix there are other members in this class of non-resonant circuits. For example, the bifilar helix has been used because it appears to lend itself easily to electrostatic focusing; however, in practice it has not been very successful in power tubes.

Another related circuit is the ring-and-bar design. This circuit is physically more rugged than the helix, and generally operates at considerably higher voltage. Therefore, it can be used at higher power levels than the helix. However, matching into and out of the ring-and-bar circuit is more of a problem than matching into and out of a helical structure.

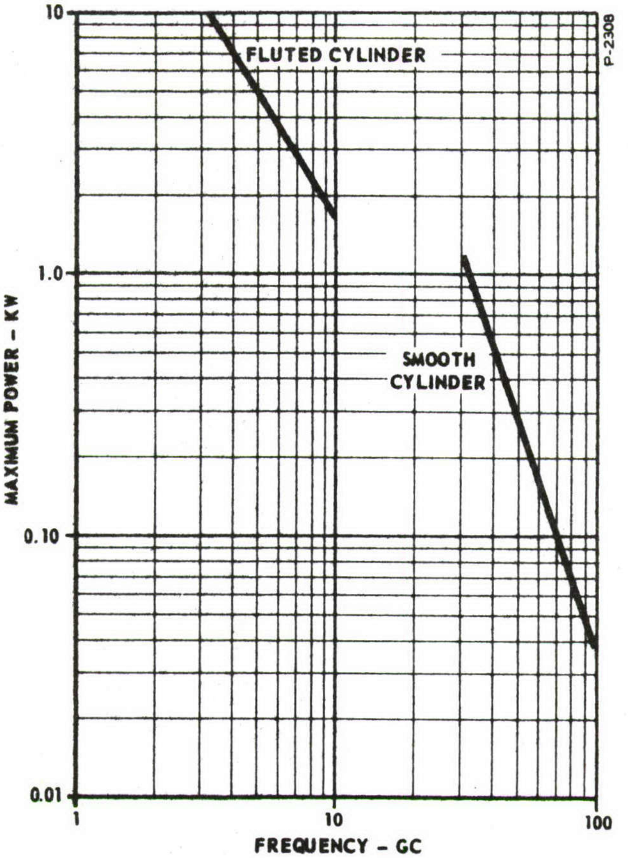


Figure 4-10 - Power Output Versus Frequency for Conduction Cooling of a Helix(89)

4.6.2.2 Resonant-Type Structures

There are other slow-wave structures, generally characterized by resonant elements, that are more mechanically and thermally rugged. This group comprises many versions of the coupled-cavity circuits and the loaded-transmission-line group, the latter including such well known representatives as the disc-loaded coaxial line, the Karp circuit, Millman circuit, etc. All of these circuits are potentially capable of high-power operation. One of them, the coupled cavity with center-hole coupling, can be electrostatically focused much in the manner of the electrostatically-focused klystron, i.e., with low-potential rings between cavities. Presumably it can be phase-velocity tapered also.

Because of their resonant nature these high power circuits generally have narrow bandwidth. Thus, the application would dictate the circuit choice.

4.6.3 Beam Collectors

For a power tube working in the space environment the handling of the kinetic energy left in the beam after it passes through the interaction region becomes difficult. There are obviously several approaches for this solution. First, of course, it would be eminently desirable to minimize the energy in the spent beam -- this would mean that the conversion efficiency is as high as possible. Regardless of the conversion efficiency attained, however, some remaining energy must still be either reclaimed or dissipated as heat. The reclamation process would utilize the depressed-potential collection techniques discussed in subsection 4.3.3. The dissipation of the energy is ultimately concerned with radiating the heat from the space capsule using a minimum amount of weight for the collection and transferral of the heat to the radiating surfaces. Some comments on this problem were made earlier such as the suggested use of high-operating-temperature radiators in subsection 4.2.3.

The best collector design is one which achieves a maximum amount of energy reclamation and dissipates the residual beam energy in as small and light-weight a package as possible.

Many depressed-potential collector designs have been discussed in the literature -- most of them become massive and bulky whenever they sort out several velocity classes in the spent beam. The mass increase is often caused by the use of magnetic components which bend the electrons along trajectories determined by their velocities.

With simplicity as the primary goal an approach to the beam-collection problem is offered for consideration by the space tube designer, although it is admitted in advance that there is presently only a limited amount of experimental corroboration to back it up. As the spent beam, with many velocity classes, leaves the interaction region it would be allowed to pass beyond the focusing structure and to spread out transversely due to space-charge forces. In this region it would then pass through a series of mesh grids operating at successively lower potentials to collect the electrons of the various velocity classes.

If nothing more is done, the mesh-type collector intercepts its geometrical shadow-fraction of current of all the velocity classes reaching the plane of the grid. Thus, it tends to overheat since its heat-conduction path is restricted. One suggested solution[90] to this problem is to coat each screen with a high-temperature insulation (e.g., Al_2O_3) on the side facing the oncoming beam. This insulating coating would charge up to a locally negative potential relative to the wire screen itself and would therefore deflect the oncoming stream of electrons and steer them through the interstices. The electrons would proceed through the screens as far as their velocities would take them, the fastest ones penetrating the farthest. Each electron would eventually slow down to zero velocity and return to the back side of the last screen it passed through, this back side being uncoated. The very fastest electrons would go through all the screens and finally collect on a plate made of refractory metal operating at a high temperature -- thereby radiating effectively to deep space.

Successful application of this collection technique awaits the quantitative evaluation of certain problems through a systematic measurement program. The secondary emitting properties of all materials used is one problem; their stability under electron impact is another. Finally, the ability to trap the turned-back electrons before they migrate all the way back to the interaction region is a subject requiring further investigation. To date preliminary experiments have been performed at Bendix Corporation Research Laboratories using a solid-beam electron gun (microperveance of 1.2) and coated screens in the assembly shown in Figure 4-11. They indicate that within limited velocity ranges the desired results are obtained.

4.7 SUMMATION ON THE DESIGN OF HIGH EFFICIENCY TWA's FOR SPACE USE

The important requirements of space tubes have been specified and the environment that they will encounter has been described. In addition some of the everpresent limitations have been discussed. In the latter study linear-beam tubes have been singled out, in particular the traveling-wave amplifier.

One must take cognizance of all the factors discussed up to this point in choosing materials, and in setting the goals and in recognizing the limitations for a design. The procedure used to translate a tube specification into an actual tube calls for an approach similar to the following:

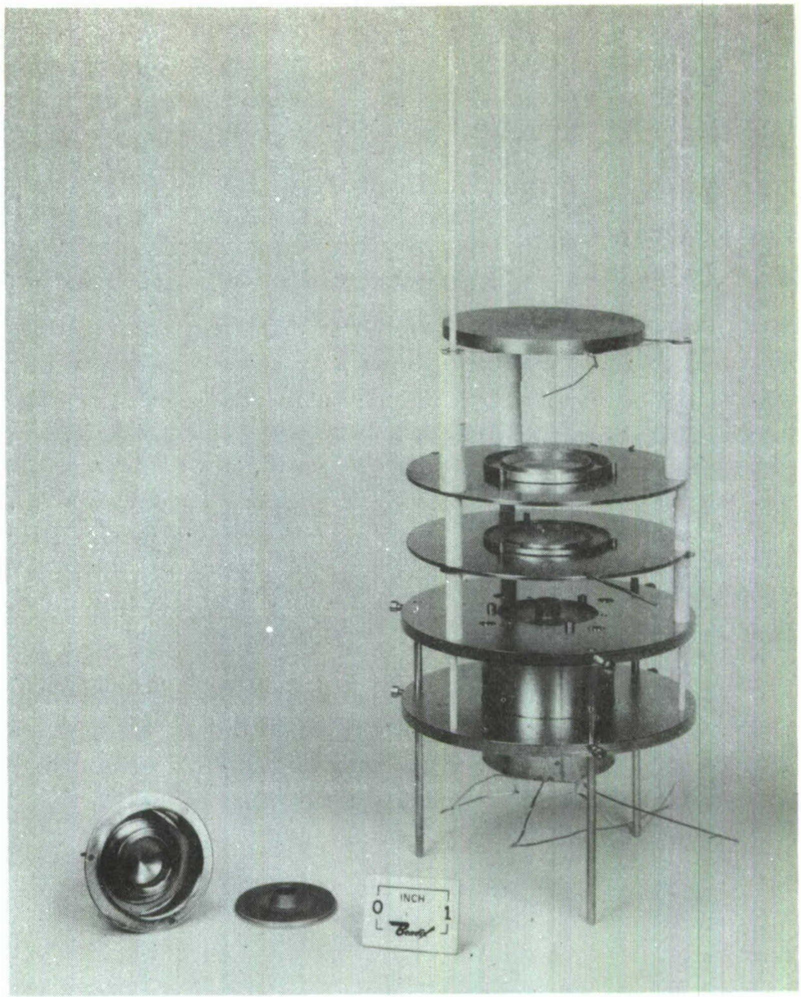


Figure 4-11 - Depressed-Potential Collector Test Assembly

A multistep program is necessary to choose the proper design with optimum efficiency for a specific application. First, a computer program based on a realistic large-signal theory of the traveling-wave amplifier with phase focusing included should be available. There are several of these now extant. With the large-signal program a sizeable number of normalized parameter sets; i.e., gain C, space charge QC, etc., can be scanned and the efficiency levels achievable by each set reported out. Some of the programs even allow the computer to choose the phase focusing profiles which give near-optimum efficiencies.

Second, an analysis of various real structures combined with practical beams is required. The aim here is to convert the physical characteristics; i.e., geometry, frequency, beam power and perveance,

etc., into the normalized parameters above. In so doing, special properties of the particular circuit-beam pairs can be brought out. For example, the bandwidth and gain characteristic of the circuit-beam pairs can be interestingly displayed as suggested by Pierce[91] and carried out by several others, most notably by Hiramatsu.[92]

The final judgment on the correct circuit-beam pair for any particular application is made by essentially overlaying the data obtained from the two sources above. This is possible since both the large-signal theory and the circuit-beam analysis are expressed in terms of the same normalized parameters.

This over-all program could be termed a Figure-of-Merit concept. Obviously the conclusions must always be tempered by the knowledge of the many practical limitations discussed earlier and must be evaluated with the particular application's most critical specifications foremost in mind.

Lastly, the space tube must always be tested in as realistic way as possible, both electrically and environmentally. The subject of pre-flight testing is discussed in detail in Section 5.

SECTION 5

PRE-FLIGHT TESTING

5.1 IMPORTANCE OF TESTING SPACE TUBES

There is an overriding requirement of reliability for an electronic payload sent aloft to perform a space mission. It is only sound logic that the mission should not be jeopardized by the failure of any electronic system or component. When the system is composed of many components, such as a solid-state computer, statistical analysis dictates that the failure rate per component must be very, very low--in the order of 0.001 percent failure per 1000 hours for a long-duration flight according to recent estimates.[93] For a major component such as a microwave tube whose performance controls the system, the mean time before first failure should be longer than the duration of the mission. Redundancy can be utilized whenever the weight penalty can be accepted.

Longevity of a major electronic component, such as a microwave tube should in theory be as long as the life of the weakest component. In a thermionic tube the cathode emission properties and possibly the heater are usually the first to deteriorate. Conservative design and conservative operating conditions for these critical parts are essential. Potential sources of damage to such sensitive components must also be found and eliminated.

Testing is carried out through all phases of the tube's evolution to a finished product. There is development testing, tube qualification testing, manufacture-proof testing (quality control), and acceptance testing for a particular mission. We are primarily concerned in this section with development and qualification tests.

5.2 TESTS

The most logical and economical approach in testing is to qualify first the constituent materials that go into the tube, then the subassemblies, and finally the finished microwave tube. Henry Maurer of NASA-Goddard[94] has expressed a similar test philosophy, which has the advantage of reasonable cost in terms of money, time and equipment.

He advocates determining probable lifetime on materials and smaller components, only. Systems testing would then be used primarily to determine compatibility of various subsystems. A convenient rule of thumb, based on NASA-Goddard's experience with scientific satellites is that reasonable design practice will give six months' life. Longer missions require high quality design throughout. Special care is needed in the area of calculating heat generation, heat transfer, and heat dissipation, since most spacecraft, for some reason or other, have been running 10 to 15°C hotter than the predicted maximum temperatures. Maurer also emphasizes the need for better definitions of failure mechanisms of the various components and subsystems. At present the thermal-vacuum environmental tests are discovering more defects than any other type of test, but, when in 19 spacecraft there are 118 component failures, one-half of them of thermal origin, there is obviously room for improved testing procedures.

We are on the threshold of a new era in testing materials for space use -- the era of combined environment testing. It is expected that in the next two years there will be a great deal of such data published, some of which will permit the use of material now rated as doubtful, while other doubtful materials will be shown to be definitely unsuitable for specific missions.

5.2.1 Testing of Materials-Suggested Sequence of Tests

In Sections 2 and 3 of this report, information has been accumulated on the composite space environment and its effects on various materials. This materials guide, derived from this study and especially Tables 3.1 and 3.2, enables one to preselect materials for specific applications. For materials on which data are not available or are incomplete, a brief description of the tests to be performed is given.

(1) Temperature Tests - Temperature limitations of the material in atmosphere (air). These tests are relatively simple to perform.

(2) Vacuum Tests - The vacuum behavior, outgassing rate of the material at room temperature is an initial prerequisite to further testing.

(3) Thermal Vacuum Tests - Thermal vacuum tests expose the material to a combined low pressure and expected or even higher temperature environment. The possible criteria for determining what constitutes failure are loss or change in physical or electrical properties, and damage due to the desorbed gases by either their presence or by their reaction with nearby components. To determine evaporation rates, weighing is necessary at given intervals after vacuum-temperature tests have been performed. It may be required to perform tests to determine whether cold welding takes place or to determine the nature of the outgassing to 10^{-7} Torr or lower which would require the use of a mass spectrometer. Rapid pumpdown, approaching that experienced in rise-to-orbit, does not appear to be as essential for materials as for components.

(4) Combined Ultraviolet - Vacuum Tests - The organic materials which will not be protected from open space by an envelope should be tested. This test can be performed with a mercury vapor lamp separated from the vacuum chamber by a quartz port.

(5) Nuclear or Van Allen Radiation Tests - Van Allen radiation resistance is usually tested by means of gamma radiation (Cobalt 60) at a gamma facility. This gives a good indication of the damage that is proportional to the total dosage of ionizing radiation.

Because of the difference in probability of penetration by gammas, protons, and electrons, gamma tests are valid for predicting surface damage or changes in thin sheets of material due to any of the three. But, gammas would tend to cause more damage to the interior of a large solid than that produced by protons and electrons.

Nuclear power source simulation would consist of reactor testing. While the spectra of the test reactors do not precisely match those of SNAP-8, still a good indication of radiation resistance can be obtained by this testing. Bendix Systems Division is currently determining the degree of equivalence between SNAP and test reactor systems with respect to neutron and gamma damage.

Both of these are accelerated tests, that is, the dose rate is much higher than would be received in actual operation. Inasmuch as total dose, rather than dose rate, is the governing factor in determining extent of damage, the accelerated test can be considered valid in these cases.

(6) Vibration and Shock Tests - Vibration and shock test results on the materials themselves are often misleading. In practice, the material may be supported or otherwise protected, or it may be joined to a dissimilar material in such a way as to make vibration more critical for the joint than for the individual materials. Therefore, it is recommended that any vibration and shock tests be performed on components, subassemblies, and completed units rather than materials.

(7) Combined Nuclear Radiation - Vacuum - Temperature Tests - This type of test is very complex and there are few facilities capable of performing such combined tests. The reactor at Battelle Memorial Institute has provisions for attaining a vacuum of 10^{-5} Torr. It does not appear feasible to require this combined test on any electron tube materials except possibly external potting compounds or wire insulation. One practical type of test would involve encapsulating candidate materials in an envelope which would be evacuated and sealed in accordance with conventional electron tube procedures.

5.2.2 Testing of Components

Components or subassemblies of an electron tube are considered to be parts such as a metal-ceramic seal, potted connector or a combination of several materials. Tests of the same nature and sequence as listed above on materials are recommended. In addition, shock and vibration tests indicative of the intended mission should be performed on all subassemblies to determine whether additional supports or design modifications are required.

5.2.3 Testing of Microwave Tubes

The tube life can be divided into three distinct environmental phases: the earth phase prior to launch, the launch phase, and the orbital phase. These may be further broken down into the following:

(1) handling

(2) transportation

(3) storage

(4) staging (or pre-launch checkout)

(5) sterilization (applicable if lunar or planetary landings are planned)

(6) rise-to-orbit

(7) orbital or space flight

(8) possible re-entry.

5.2.4 The Earth Phase Prior to Launch

5.2.4.1 Handling, Transportation, and Storage

With the exception of the sterilization treatment, when applicable, the electron tube package for a satellite would not be exposed to any new or different environmental stresses prior to launch than experienced by equipment for airplanes and missiles. Therefore, the tests required of these equipments would be adequate. For example, if one followed the tube from the manufacturer to the launch site, normal modes of transportation would be rail, air, or truck; and handling, delivery, and storage would be controlled. The following environmental ranges are deemed as severe as would be encountered in these phases:

(1) Temperature range from -35°F to 140°F (as in air transport).

(2) Altitude - from sea level to 50,000 feet.

(3) Humidity - relative humidity up to 100 percent such that condensation takes place in the form of water or frost.

(4) Shock - handling shocks (as might be encountered by two men depositing a case) - free drops of up to one inch and pivot drops up to four inches.

Shipment shocks may result in acceleration peaks of the order of 100 g's.

(5) Vibration - as given by paragraph 4.6.8 of Mil-E-4970.

(6) Storage - environmental control would be exercised during storage to insure no performance degradation when stored for as long as one year.

5.2.4.2 Installation and Pre-Launch Environment

There would be a period of time prior to launch during which the environment would be partially controlled, but nonetheless, certain test site environment can be troublesome such as the environment encountered at Cape Kennedy. The tube package should be able therefore, to withstand the following:

(1) Temperature and Humidity - Surrounding air temperature will range from a minimum of 25°F to a maximum of 98°F. The air temperature in nonairconditioned compartments will range from 25°F to 140°F. Relative humidity up to 100 percent for nonairconditioned compartments will be experienced. Air conditioning will be supplied to control the satellite thermal control surface mean temperature in the range of 40°F to 75°F at less than 50 percent humidity.

(2) Fungus - Fungus exposure is equivalent to 28 days exposure to selected fungi as described in Mil-STD-810.

(3) Sand and Dust - Exposure to graded wind-blown sand and dust, equivalent to exposure for 6 hours in a sand and dust chamber as described in Mil-STD-810.

(4) Tolerance to r-f interference must be no worse than limits set by Mil-I-26600.

(5) Explosive atmospheres may be encountered and the package must operate in it without producing ignition of same.

(6) Salt fog may be present in coastal regions.

5.2.5 Sterilization

This treatment has been described earlier. Due to its limited application it will not be discussed further at this time.

5.2.6 The Rise-to-Orbit Phase

This very important and unique phase deserves special attention. During this concentrated time period of 8 to 10 minutes, there is a unique composite environment consisting of changing temperature, pressure, vibration, shock, and acoustic field.

5.2.6.1 Ideal Way of Testing for Rise-to-Orbit

In order to simulate the launch conditions faithfully and to test realistically, it would be necessary to obtain stress profiles versus time for the various parameters. Charts can be prepared versus time from lift-off for the corresponding 8 minutes or so until orbit or space flight is achieved plotting stress variation of the above environments.

A very recent publication[95] on a NASA contract has tabulated this kind of information for several launching vehicles of two types: sounding rockets and unmanned spacecraft.

The following parameters, plotted versus time from launch, are included in the profiles: acceleration (longitudinal and lateral), pressure, vibration, acoustics, heating, and spin. From these profiles, an over-all envelope of launch environmental parameters has been constructed. The summarized levels of environmental parameters are classified primarily by spacecraft weight.

The procedure in analysis of the stress-profile data would be to superimpose the time plots in order to determine the worst case combination of stresses. This simultaneous worst case combination would then ideally be simulated in a test chamber.

Obviously, it would be quite difficult to combine all, or even several, of the required stresses into a single test setup, but it is felt that an attempt should be made to combine at least the effects of decompression, temperature change, and vibration. This would mean that the tester would be a vacuum chamber which in turn has a vibration transducer, vacuum-seal-coupled through the bottom. The chamber would be capable of rapid pump-down although not necessarily to real hard vacuum. The walls would have heater elements to simulate satellite skin heating on rise-to-orbit simulation.

Special ports would permit d-c and r-f operation with continuous monitoring if such is required of the tube. It would be desirable to induce ionization to simulate the ion sheath condition that might be conducive to corona and voltage breakdown.

5.2.6.2 Alternate Testing for Rise-to-Orbit Phase

The combined stress-versus-time profiles during launch are difficult to define, especially for the payload locations of interest. It is also conceded that building a tester to duplicate the combined environments is a formidable task, although the magnitude of difficulty for small packages is significantly less than for systems and subsystems. Often it has been the choice of workers in this area to adopt sequential tests believing that the effects due to interaction between environments are small. Typical launch-to-orbit stresses, which will vary depending upon the booster-rocket-payload location combination, are

(1) Temperature range -- 25°F to 125°F at less than 50 percent humidity.

(2) Acoustic Field - For several seconds after lift-off acoustic excitation extending over a broad spectrum will be encountered. The sound pressure will be quite random. The maximum anticipated octave band levels are tabulated in Table 5-1.

To test the tube package one would suspend the tube elastically in a reverberation chamber and subject it to a broad-band sound field, with an over-all sound pressure level of 152 db (ref. level: 0.002 dynes/cm^2). The octave band pressure levels would be as shown. The acoustic environment would typically be applied for a period of 2 minutes.

(3) Vibration - Table 5-2 presents an example of a specific complex vibration environment due to acoustic field and structure-borne coupling which has been measured at lift-off.

Neff and Montes de Oca[94] have reported vibration flight levels for various pay loads. For instance, Table 5-3 refers to summarized levels for 1000 lb payloads.

For payloads up to 500 or 600 pounds, Neff and Montes de Oca[95] point out that in addition to sinusoidal acceleration of the usual type, it is necessary to consider the large accelerations that can arise from rocket motor resonance burning -- specifically the X-248 motor which is the final stage for Delta, Scout, Javelin, and Journeyman vehicles. This motor has burning resonances at approximately

Table 5-1 - Maximum Anticipated Octave Band Levels

Maximum Anticipated Octave Band Levels	
Octave Band (cps)	Sound Level (db)
over-all	152
37.5-75	140
75-150	143
150-300	145
300-600	147
600-1200	145
1200-2400	142
2400-4800	137
4800-9600	130

P-2308

Table 5-2 - Typical Vibration Levels

	Sinusoidal Vibration			Random Vibration - Gaussian	
Frequency Band	5-100 cps	100-300 cps	300-3200 cps	20-300 cps	300-2000 cps
Vibration Level	5 g. rms	5 g. rms	5 g. rms	0.04 g^2/cps*	0.16 g^2/cps*

P-2308

*Random vibration rolls off at a rate of 12 db/octave from 1200 to 2000 cps

Table 5-3 - Vibration Levels for Payloads of Approximately 1000 lbs

Longitudinal	10-250 cps	±2.5 g. (peak sinusoidal)
	250-400 cps	±3.3 g. (peak sinusoidal)
	400-2000 cps	±5.0 g. (peak sinusoidal)
Lateral	10-250 cps	±1.5 g. (peak sinusoidal)
	250-400 cps	±2.0 g. (peak sinusoidal)
	400-2000 cps	±5.0 g. (peak sinusoidal)

P-2308

Table 5-4 - Burning Resonance Levels - SCOUT (150 lb Payload)

Longitudinal	580 cps	to 18 g. rms
	1160 cps	to 9 g. rms
	2350-3700 cps	to 29 g. rms
Lateral	580 cps	to 6 g. rms
	1160 cps	to 3 g. rms
	2350-3700 cps	to 52 g. rms

P-2308

580 and 1160 cps and also a range between 2350 and 3700 cps. While these burning resonances are of only a few seconds duration, magnitudes of vibration are very high.

It is possible that rocket motors having burning resonances similar to those of the X-248 (although perhaps in different frequency ranges) can be used.

Table 5-4 lists burning resonance levels which were measured on a Scout test (150 pound payload).

While it would be advisable to test the electronics package under all the expected worst case environments of the types and magnitudes above, a typical acceptance test for the environment specified in Table 5-2 has in at least one instance been modified as follows:

The tube package shall be vibrated as follows: from 5 to 100 cps, 2 g rms; from 100 to 1000 cycles, 5.5 g rms. The vibration shall be sinusoidal and limited to 0.4 inch double amplitude. The vibration shall be applied in each of three coordinate directions and shall be swept at one octave per minute. Performance parameters shall be monitored during vibration. The equipment shall operate throughout without failure or malfunction. The vibration shall be applied and measured at points of attachment to the structure.

(4) Shock - Shocks caused by booster ignition and cut-off will occur. Maximum shock loads of 30 g with an 11 millisecond pulse will be experienced. Later in ascent shock loads of 100 g with a 6 millisecond pulse will be experienced.

(5) Temperature - A temperature range from 25°F to 125°F will be experienced. If the tube is near the satellite shell and is unprotected, then effects due to skin heating could be more severe.

(6) Continuous Acceleration - While operating, the equipment shall be centrifuged for at least three minutes in each direction along the three coordinate axes as follows: Forward longitudinal 20 g; reverse longitudinal, 20 g; plus and minus pitch and yaw, 20 g.

5.2.7 Orbit or Space Phase - Tests to Simulate Same

Once in orbit the tube must perform over a long life in the space environment. Therefore, the tests needed are essentially life tests or at least, life-predicting tests for the expected environment.

5.2.7.1 Thermal-Vacuum Testing

The most important test is the thermal-vacuum test. Many electron tubes find this a difficult hurdle. In brief, this consists of operating the tube at rated power in a vacuum simulating the thermal isolation it would experience in orbit and observing the temperature that critical parts of the tube assume and also observing the r-f output. The heat sinks would be programmed to faithfully simulate the expected variation to be encountered.

For example, the tube would be operated at a maximum pressure of 1×10^{-6} mm Hg while the conduction and radiation sink temperature is increased to 135°F and maintained for a period of five (5) hours. Following this, the conduction and radiation sink temperature would be reduced to 15°F within one hour and maintained at that temperature for five (5) hours. This cycle shall be repeated ten (10) times typically.

5.2.7.2 Long-Duration Life Tests with Several Samples

The thermal-vacuum test would of necessity be extended to long duration and with enough samples to establish statistical reliability whenever practicable. One year minimum is a frequently quoted time scale. The longer the better.

5.2.7.3 Cathode "Dip" Test

A shorter test will give an advanced indication of potential tube life as it is affected by the cathode life only. The test is as follows: The tube is operated in a normal manner in its expected environment, (in this case in vacuum), but the heater current is turned off and on cyclically. The total emitted current is monitored throughout. The amount of dip in the current following heater turn-off and the subsequent length of time required for recovery can be related to expected cathode life when compared with previous histories of cathodes of the same type. This is a good test and can be useful in space tubes.

SECTION 6

CONCLUSIONS - NEW CONCEPTS

6.1 TOPICS CONSIDERED

This report has attempted to look ahead to the next generation of space tubes. No specific missions were in mind; however, interest centered on one class of tubes, viz., CW amplifiers operating from about 1 Gc at 10 kilowatts to 10 Gc at 100 watts.

Initially, the expected environment of space, both natural and artificial, was carefully catalogued. In connection with this study, a special treatment for calculating the ionizing radiation in the Van Allen and artificial belts has been given in Appendix A, with assumptions and the degree of their uncertainty. The effect of the over-all environment on the constituent materials of the space tube package was then evaluated and materials were given a preference ranking.

Next, the design of the tube was considered. Linear-beam tubes and in particular traveling wave amplifiers were given the most attention. The essential properties required of a space tube were enumerated and procedures for achieving them discussed, in some detail. Limitations and problem areas that bound the designs were pointed out. Some new concepts will be advanced later in this Section.

The importance of adequate pre-flight testing was emphasized. A philosophy of combined-environment testing was advanced, and sequential testing, as a substitute, was also discussed.

6.2 GENERAL CONCLUSIONS

The most important attributes of a space tube, emphasized several times in this report, are a high degree of reliability, high efficiency, and low mass. The design of tubes to achieve these properties calls for the selection of suitable materials, adherence to sound design practice, carefully-controlled fabrication, and well conceived flight testing.

New and exotic approaches to space tube design must always be viewed in the context of the tube's place in the system and vehicle and

the planned mission. For example, it may be advantageous to open the tube's envelope in space but only if entry or re-entry into a planetary atmosphere will not subsequently be encountered. An orbiting TV transmitter could be so designed; a Mars probe could not.

The major investigations during the next few years will probably concern the following areas.

6.2.1 Improving Reliability

The materials used in the tubes must be carefully chosen but this seems to pose no serious problem in view of the study of Sections 2 and 3 where the materials are given relative ratings. The best ceramic-metal tubes designed for rugged military use should be reliable in a space environment. Glass envelope tubes in this power range with their attendant heat dissipation problems would be less suitable choices.

Certain precautions are always necessary. The heat sinks available to the tube must be well known in advance and integrated into the tube design to make sure that the tube will not fail under continuous operation in the isolated thermal environment. This must then be proved out in the testing program.

If the heat sinks available are not adequate, the tube design may have to utilize a very hot collector radiating into space. High temperature metal-ceramic seals must be developed and utilized.

Beam focusing must be sufficient to prevent beam interception of a magnitude which is detrimental to either the interaction structure or the cathode through poisoning. In general, electrostatic focusing will have to prove itself in power tubes by life tests. The electrostatically-focused klystron should be the best candidate to start with because of its rugged interaction structure.

6.2.2 Improving Efficiency

It cannot be stressed too strongly that there should be a great deal of effort devoted to designing space tubes (particularly TWA's) with enhanced conversion efficiencies. In principle, and in practice, the way has been charted; it lies in the utilization of phase focusing or locking of electron bunches and circuit fields.[84] Conversion efficiencies of 40 to 50 percent and perhaps higher can be achieved in a TWA operating over a substantial bandwidth.[85].

Plate-circuit efficiency improvement is recommended when the trade-off in complexity of power supply and additional component size and weight is reasonable. Depressed-potential beam collection of one or two stages in linear-beam tubes would usually fall into this category.

Heat-to-electrical-power converters will probably require a few more years of development. The basic efficiency of these converters, i.e., the thermionic, thermoelectric, and Peltier junctions, are between 7 and 15 percent; they also require careful temperature control and heat rejection at possibly a lower temperature. Thus, the recovery of waste power through these methods needs careful scrutiny in any particular case before designing these devices into the tube.

6.2.3 Reducing Mass of Entire Tube Package

The approach to low mass is severalfold: the design must strive for high efficiency, optimum tube size, compact and efficient power supplies, and low-weight focusing structures.

The first two of these choices are clearly under the control of the tube designer while the other two are influenced by his parameter choices. Magnet weight will be influenced further by the development of new magnetic materials. The designer must keep abreast of this area and must also be aware of improved power-supply components and designs.

6.2.4 Testing

In some ways the space application parallels the submarine cable problem, i.e., the tubes once in use are essentially inaccessible to later maintenance or adjustment; hence, they are expected to have long life. Therefore thorough testing is required.

The expected environment should be simulated as closely as possible and the tube package's survival potential should be evaluated in this synthesized environment.

Life tests are a must; the more closely the life test approaches the real mission in environmental conditions and duration, the more confidence one can place in the reliability of the results. A statistically valid number of tubes presumably would be life tested.

6.3 NEW CONCEPTS

Two categories are discussed. The first is the exploitation of schemes specifically suited to the space application, but applied to present tube types. The second is new tube designs that seem to be suggested by the space environment.

6.3.1 Adaptation of Present Tube Types for Some Space Applications

Our thoughts again turn to methods for improving the reliability and efficiency and reducing weight. Consider once more a traveling-wave amplifier and let us make the following summarizations.

6.3.1.1 Tapered-Parameter TWA's

Suggestion number one would be to build a higher-conversion-efficiency family of tubes by carefully applying the phase focusing principle; for example, the tapered-circuit-velocity approach. Indications of significant improvement justify further effort along these lines.

6.3.1.2 Sophisticated Depressed-Potential Collectors

Inventive minds will come up with depressed-potential collector designs that are favored by the space environment. There is the temptation to eject the beam from the tube into space with ultimate collection on the outer skin of the satellite, hopefully at reduced potential. This collection scheme cannot be dismissed in all cases but by the same token it poses problems of its own. The depression cannot be too much or the electrons will not emerge from the satellite. Then too, the collection of electrons on the satellite may cause interference with sensing devices, may cause r-f transmission difficulties, or may induce voltage breakdowns, etc.

Perhaps a better design might allow the collector to unfold in space allowing beam spreading to accomplish velocity sorting and collection over a long distance but still essentially confined. This presupposes that the envelope can be opened in space, an operating condition only acceptable in those missions that avoid planetary atmospheres and in those payload locations not subject to an outgassing environment.

Coating the surface of mesh-type collectors with insulation on the side facing the impinging beam should have the advantage of reducing interception on the wire surfaces, thereby enhancing the completeness of depressed-potential collection. This technique must still be proved practical over higher ranges of beam power.

6.3.1.3 Thermal-Electrical Converters

Thermionic or thermoelectric converters heated by the spent beam power would be useful if their efficiencies could be improved significantly above the present average of 12 percent. Until then, they do not seem promising since the additional components required and the necessity for temperature control lead to considerable complication of design.

6.3.1.4 Tandem Tubes

The spent beam emerging from a driver-tube could conceivably be used to heat the cathode of the succeeding power stage, thereby reclaiming the beam energy and doing away with the heater on the second tube. This design merits further investigation.

6.3.1.5 "Cold" Cathodes

Efficiency and reliability together may be enhanced through the use of "cold" cathodes such as the tunnel and point field emitters. The formation of beams of high conductance and power by these approaches still requires much development effort. Looking farther ahead, one must hope that these devices will ultimately come into their own. Potentially they are the ideal space cathodes.

6.3.2 New Tube Types

6.3.2.1 Integrated Circuit and Antenna Concept

The high vacuum of space, when it can be utilized, suggests the removal of the tube envelope and the consolidation or combining of antenna and interaction circuit without need for vacuum r-f connectors, etc. If high-vacuum environment cannot be counted on, the idea can still be used by housing the entire tube in an evacuated radome with only d-c vacuum leads and perhaps one r-f lead emerging.

A circuit-antenna design for a TWA that intuitively seems compatible with the integrated concept would be the helix (probably bifilar) and the log periodic spiral antenna. Preliminary consideration of such a design has been started.

6.3.2.2 Beam Spreading Tube

For low power applications it should be possible to build a lightweight traveling-wave amplifier whose slow-wave circuit has been sculptured along its length to conform to the diameter of a beam emanating from a converging gun, necking down to a minimum and then expanding again.

6.3.2.3 Severed Helix TWA with Electrostatic Lens Correction

Enlarging upon the above tube and in line with recent successful electrostatically focused klystron development (e.g., the Litton ESFK)[96] it would be feasible to consider a parallel approach for the TWA. Such a tube would consist of two or three sections of TWA circuit with ring type lens electrodes at the severs. A certain amount of beam spreading could be tolerated within each section with radial velocity compensation at each subsequent sever.

SECTION 7

REFERENCES

1. J. G. Meeker, "Investigation of Techniques for Space-Oriented Tubes," RADC-TDR-64-7, January 1964.
2. Wilber L. Pritchard, (Aerospace Corp.), Microwave Journal, 6, No. 8, 52 (Aug. 1963).
3. Hearings before the NASA Authorization Subcommittee of the Committee on Aeronautical and Space Sciences, United States Senate 86th Congress, Second Session on H.R. 10809 June 30, 1960. Part 2 of Scientific and Technical Aspects of NASA Program, p. 680.
4. L. D. Jaffe and J. B. Rittenhouse, "Behavior of Materials in Space Environments," JPL Technical Report 32-150, also in ARS Journal, 32, 320, (March, 1962).
5. E. G. Jackson, Wear, 5, 417, (1962).
6. M. P. Hnilicka and K. A. Geiger, Astronautics and Aerospace Engineering, 1, 31, (July, 1963).
7. "Space Radiation Effects on Materials," STP330, ASTM, Philadelphia, 1962.
8. F. S. Johnson (editor), "Satellite Environment Handbook," Stanford University Press, Stanford, California, 1961.
9. C. A. Barth, "Atomic Reactions in the Upper Atmosphere of Earth, Mars and Venus," 12th International Astronautical Congress Proceedings; vol. 1, 1961, p. 498-500.
10. Anon., Astronautics and Aerospace Engineering, 1, 127, (June 1963).
11. S. F. Singer, Chapter 13 of "Space Science" ed. by D. P. LeGalley, John Wiley & Sons, N.Y., p. 522 et seq.
12. W. W. Kornemann, "Proceedings of Bendix Extreme Environment Program," November 27 & 28, 1962, p. 10-1
13. D. J. King, "Properties of the Atmosphere Revealed by Satellite Orbits," in Progress in Astronautical Sciences (S. F. Singer, ed), North Holland Publishing Co., Amsterdam, 1962, Vol. I, p. 40.

14. F. L. Whipple, Journal Geophysical Research, 68, No. 17, 4929, (September 1, 1963).

15. C. T. D'Aiutolo, "First Meteoroid-Penetration Data for SNAP Designers," Nucleonics, 21, No. 11, 51 (November 1963).

16. NASA News Release 63-203, September 15, 1963.

17. National Academy of Science, IG Bulletin No. 69 in Transactions American Geophysical Union, 44, 648, (March 1963).

18. "Handbook of Chemistry and Physics," 43rd Edition, Chemical Rubber Publishing Co., Cleveland, 1962, p. 2802.

19. B. J. O'Brien, Scientific American, 208, 84, (May 1963).

20. Anon., Transactions American Geophysical Union, 44, 255, (March 1, 1963).

21. J. E. Naugle, "Results in Scientific Research in Space," Proceedings of the NASA - University Conference on Space Age Planning, Chicago, May 6-9, 1963, Vol. 1.

22. Anon., "Additional Status Report on Trapped Electrons from the Starfish High Altitude Nuclear Test," - Joint Report of AEC, DOD and NASA, February 4, 1963.

23. Remarks from the floor, 10th Annual East Coast Conference on Aerospace and Navigational Electronics, October 21-23, 1963, Baltimore, Maryland.

24. M. C. Chapman, R. E. Fortney, and M. R. Morrison, "Comments on the Production of Solar High Energy Particles," Proceedings of the Symposium on the Protection Against Radiation Hazards in Space, Gatlinburg, November 5-7, 1962, p. 96.

25. L. R. Lewis, "Solar Flare Satellite Design," Bendix Systems Division BSC39803, ATWL-TDR 63-3010, August 1963.

26. C. E. Fichtel, D. E. Guss and K. W. Ogilvie, "Details of Individual Particles Events," Proceedings of the Symposium on the Protection Against Radiation Hazards in Space, Gatlinburg, Tenn., November 5-7, 1962, p. 44.

27. H. H. Malitson and W. R. Webber, Solar Proton Manual, NASA Technical Report R-169, September 1963, p. 12.

28. P. Higgins, NASA, "Apollo Space Radiation Warning System," A talk given at University of Michigan-IES joint lecture series on Environmental Sciences, February 26, 1964. Also to be published in 1963 Proceedings of Institute of Environmental Sciences, Philadelphia, April 13-15, 1964, as part of paper by B. Baker and P. Higgins.

29. J. W. Keller, NASA, "Solar Radiation in Space," A talk given at University of Michigan-IES joint lecture series on Environmental Sciences, February 26, 1964.

30. Anon., Missiles and Rockets, 14, 7, (March 16, 1964).

31. W. Biler, Missiles and Rockets, 14, 22 (March 23, 1964).

32. D. McKeown, "Surface Erosion in Space," July 14, 1962 - N62-16269 General Dynamics/Astronautics.

33. F. S. Johnson and W. L. Webb, Astronautics and Aerospace Engineering, 1, 84 (November 1963).

34. W. F. Dudziak, D. D. Kleinecke, T. J. Kostigen, "Graphic Displays of Geomagnetic Geometry," RM63TMP-2, DASA 1372, April 1, 1963.

35. Anon., (NASA) Annex B, Request for Proposal for Apollo. See also, "The Lunar Atmosphere," by E. J. Öpik, Tech Report 240, University of Maryland Physics Dept., NASA Grant NSG-58-60.

36. T. Gold, Journal Geophysical Research, 64, 1798, (1959).

37. W. M. Sinton, "Temperatures of the Lunar Surface" in "Physics and Astronomy of the Moon," Academic Press, N.Y., 1962, p. 408.

38. A. H. Barrett and A. E. Lilley, Sky and Telescope, 25, No. 4, 192, (April 1963).

39. NASA News Release 63-36-1, February 26, 1963.

40. S. I. Rasool, AIAA, 1, 6, (January 1963).

41. Douglas Aircraft, "Physical Properties of the Planet Mars," Douglas Report SM-43634, p. 53.

42. Anon., Nucleonics, 21, 79 (July 1963).

43. J. Edmonds, "Relations Between Electronic Techniques and Over-all Weight of Electronic Subsystems for Nuclear Electric Space Vehicles," 1963 Proceedings National Aerospace Electronics Conf., p. 13-23.

44. C. E. Johnson and C. A. Goetz, AIAA, 1, No. 10, 2355 (October 1963).

45. L. D. Jaffe, Astronautics and Aerospace Engineering, 1, 22 (August 1963).

46. F. A. Morelli, F. Fehner and C. Stembridge, Nature, 196, No. 4850, 106 (October 13, 1963).

47. I. Stambler, "High Temperature Materials," Space/Aeronautics, 40, 31 (November 1963).

48. W. E. Chapin, "The Effect of Nuclear Radiation on Electron Tubes and Tube Materials," REIC Report 14, February 15, 1961.

49. F. G. Schmidt, "Research and Investigation on Radiation Resistant High Temperature Thermionic Circuitry," ASD-TDR-62-1039.

50. D. S. Billington and J. H. Crawford, "Radiation Damage in Solids," Princeton University Press, Princeton, N.J., 1961, p. 237.

51. R. G. Wheeler, "Neutron Irradiation of Sapphire (Al_2O_3)," Hanford Atomic Products Operation, Report No. HW42022 (March 1956).

52. J. A. Baicker, B. W. Faughnan, and P. Rappaport, "Radiation Damage in Silicon Solar Cells," RCA Contract No. NAS, 5-457, 1961.

53. J. A. Baicker and P. Rappaport, "Radiation Damage to Solar Cells," Paper B-1, Proceedings of Symposium on Radiation Hazards in Space, Gatlinburg, Tenn., November 5-7, 1962.

54. F. R. Shober, "The Effects of Nuclear Radiation on Structural Metals," REIC Report 20, September 15, 1961.

55. M. K. Cooper, A. R. Palmer and G. Z. A. Stolarski, "The Effect of Neutron Irradiation on the Thermal Conductivity of Beryllium Oxide," Journal of Nuclear Materials, 9, No. 3, 320-326 (1963).

56. N. E. Wahl, R. R. Lapp and F. C. Haas, "The Effects of High Vacuum and Ultraviolet Radiation on Nonmetalic Materials," WADD 60-125, Part II, June, 1963.

57. A. M. Bishay, J. American Ceramics Society, 45, (8), 389, (August 1, 1962).

58. W. E. Price, E. E. Gaines, D. Newell and E. B. Pearson, "Space Materials Handbook," Lockheed Missiles & Space Co., AF-04(647)-673, January 1962, p. 443.

59. K. Yamamoto and M. Tsuchiya, Journal of Applied Physics, 33, (10), 3016, (October 1962).

60. J. D. Fleming, American Ceramic Society Bulletin, 41, (7), 472, (July 15, 1962).

61. E. V. Kolontsova and I. V. Telegrina, Akademia Nauk, SSSR, Doklady 147, 592 (November 1962) and translation, Soviet Physics Doklady, 2, 1034 (May 1963).

62. E. R. Pfaft, "Effects of Nuclear Radiation on Electronic Components," WADC-57-361, Volume V, November 1962.

63. D. H. Buckley, M. Swikert and R. L. Johnson, ASLE Transactions, 5, (1), (April 1962), p. 8.

64. F. R. Shober and W. E. Murr, "Experimental Investigation of Radiation Induced Property Changes in a Particular Type of Stainless Steel," Presented at the Fourth ASTM - Pacific Area Meeting at Los Angeles, October 1-5, 1962, Paper 121.

65. N. E. Hinkle, "Effect of Neutron Bombardment on the Stress Rupture Properties of Some Structural Alloys," Presented at The Fourth ASTM - Pacific Area Meeting at Los Angeles, October 1-5, 1962, Paper 122.

66. D. I. Gordon and R. S. Sery, "Effects of Charged Particles and Neutrons on Magnetic Materials," IEEE Summer General Meeting, Toronto, June 16-21, 1963, Subsequently published in IEEE Transactions on Nuclear Science, NS-10, No. 5, 20 (November 1963).

67. D. I. Gordon, Electro-Technology, 67, (1), 118, (1961).

68. V. L. Lanza and E. C. Stivers, "An Improved Insulation for Space Use," Electronic Industries, 22, 100, (July 1963).

69. Philip J. Klass, "Survivability of Wire on Moon Tested," Aviation Week - Space Technology, 78, 77, (May 27, 1963).

70. Anon., "Tiros and Teflon are Top Hat as World Weather Eye," Journal of Teflon, 4, 1, (July-August 1963).

71. S. Podlazeck and J. Sukorsky, "The Stability of Organic Materials in Vacuum," Institute of Environmental Sciences, 1963 Proceedings, Los Angeles, April 17-19, 1963.

72. D. J. Hamman and Walter N. Veazie, Jr., "Report on Survey of Irradiation Facilities," REIC Report 31, Part 1, September 15, 1963, p. 24.

73. R. W. King, N. J. Broadway and S. Palinchak, "Report on the Effect of Nuclear Radiation on Elastomeric and Plastic Components and Materials," REIC Report 21, September 1, 1961.

74. C. E. Jolley and J. C. Reed, Space Aeronautics, 39, 105 (February 1963).

75. R. Harrington, "Elastomers for Use in Radiation Fields," Available as a single report combining papers which appeared in Rubber Age, 81, 971 (1957), Ibid., 82, 461, (1957), Ibid., 82, 1003, (1958), and Ibid., 83, 472, (1958).

76. R. R. Leppla and R. R. Carrger, Insulation, 9, 35, (June 1963).

77. V. J. Linnenbom, "Radiation Effects on Insulation -- State of Art," Insulation, 10, No. 3, 21, (March 1964).

78. E. T. Smith, "Measurement of the Combined Effects of Nuclear Radiation and Cryotemperatures on Non-Metallic Spacecraft Materials," Paper 63-1175, AIEE Summer General Meeting, Toronto, June 17-21, 1963.

79. A. O. Burford, "Results of Radiation Test on Materials and Components for Nuclear Rocket Applications," American Nuclear Society Transactions, 6 No. 2, 302 (November 1963).

80. L. J. Frisco, A. M. Muhlbaum, E. A. Szymkowiak, "Dielectrics for Satellites and Space Vehicles," covering the period March 1, 1962 through March 31, 1963, AD-409168.

81. A. P. Bonnani, "The Effect of Gamma Irradiation and High Vacuum on Polymeric Materials," AD-417065, August 20, 1963.

82. I. Welber, Astonautics and Aerospace Engineering, 1, 68 (September 1963).

83. S. C. Rogers, " Methods of Predicting the Performance on Semiconductor Electronic Circuits and Systems in a Nuclear Environment" Institute of Environmental Sciences, 1963 Proceedings, p. 129.

84. J. G. Meeker and J. E. Rowe, IRE Transactions of the Professional Group on Electron Devices; ED-9, No. 3, 257 (May 1962)

85. J. E. Rowe and C. A. Brackett, "Efficiency, Phase Shift and Power Limiting in Variable-Pitch Traveling-Wave Amplifiers," Paper presented at the 18th Annual National Electronics Conference, Chicago, Illinois, October 8, 9, 10, 1962.

86. A. G. Peifer, Bendix Corporation Research Laboratories Division, unpublished study.

87. L. F. Eastman, "Super-Power Microwave Tubes," Invited Paper at Electron Devices Conference, Washington, D.C., October 31, 1963.

88. A. H. W. Beck, "Space Charge Waves," Pergamon Press, New York, 1958, p. 344.

89. H. K. Detweiler, et al., "Applied Research on High-Thermal-Conductivity Materials for Use in Microwave Tubes," ASD-TDR-62-153 Electron Physics Laboratory, Department of Electrical Engineering, University of Michigan, December 1961, p. 41.

90. K. C. Earl, Bendix Corporation, Research Laboratories Division, by Private Communication.

91. J. R. Pierce, "Traveling-Wave Tubes," D. Van Nostrand, New York, 1950, p. 85.

92. Yukio Hiramatsu, "A Study of High-Power Traveling-Wave Tube Circuits," ASD-TDR-62-854 Under Contract No. AF 33(616)-7623, Varian Associates, January 1963.

93. J. Hornbeck, "Electron Devices In Space Application" - Luncheon speech at Electron Devices Meeting, IEEE, Washington, D.C., October 31, 1963.

94. Henry Mauer, "Space Vacuum Investigations," presented at University of Michigan - IES Joint Lecture Series on Environmental Sciences, February 26, 1964.

95. W. J. Neff and R. A. Montes de Oca, "Launch Environment Profiles for Sounding Rockets and Spacecraft," Booz-Allen Applied Research, Inc,, Bethesda, Maryland, (Contract NAS 5-2415, for sale by the Office of Technical Services, Department of Commerce, Washington, D.C., 20230.) January 1964.

96. J. R. Hechtel and A. Mizuhara, " Recent Advances with the Electrostatically Focused High Power Amplifier Klystrons," Electron Devices Meeting, Washington, D.C., October 31 - November 1, 1963.

97. J. A. Van Allen et al., Jet Propulsion, 58, p. 588, September 1958.

98. "Space Radiation as an Environmental Constituent," Radiation Effects Information Center, REIC Memo 19, Battelle Memorial Institute, January 15, 1960.

99. Johnson, "Satellite Environment Handbook," p. 55.

100. W. N. Hess, International Science and Technology, No. 21, pp. 40-48, September 1963.

101. W. N. Hess, remark from the floor, Tenth Annual East Coast Conference on Aerospace and Navigational Electronics, October 21, 1963.

102. S. Tilson, International Science and Technology, No. 13, pp. 20-31, January 1963.

103. Johnson, "Satellite Environment Handbook," p. 123.

104. L. Katz and A. S. Penfold, Reviews of Modern Physics, 24, p. 28, 1952.

105. "Space Radiation and Its Effects on Materials," Radiation Effects Information Center, REIC Memo 21, Battelle Memorial Institute, June 30, 1961.

106. R. D. Evans, "The Atomic Nucleus," McGraw-Hill Book Co., Inc., p. 742, 1955.

107. S. C. Lind, "Radiation Chemistry of Gases," Reinhold Publishing Corp., New York, New York, pp. 15 and 17, 19, 1961.

108. Evans, op, cit., p. 617.

APPENDIX A

AN ESTIMATE OF RADIATION EXPOSURE DUE TO THE VAN ALLEN BELTS

A-1 INTRODUCTION

This Appendix discusses the requirements that must be considered in designing satellite components or systems which may be exposed to the ionizing radiation environment of the Van Allen Belts. That this environment is damaging has been demonstrated by the failure of transistors and solar cell power supplies on many satellites. On the other hand, shielding, material substitution, or allowance for performance degradation can be utilized to provide suitable lifetimes when the type, flux, energy, and location of ionizing particles are known.

The Van Allen Belts and the artificial radiation belt are briefly described in this report. Assumptions necessary to calculate the ionizing radiation exposure are included to show the degree of uncertainty attached to such calculations. The radiation exposure for equatorial orbits (to 60,000 km altitude) is calculated for the surface of a satellite. The effect of 1 gm/cm^2 of aluminum shielding is also described.

A-2 THE VAN ALLEN BELTS

The Van Allen radiation belts consist of high energy charged particles (both electrons and protons) trapped in the earth's magnetic field. Evidence of this trapped radiation was first discovered by Explorer I[97] in January, 1958. Data from early satellites and sounding rockets indicated that trapping did not occur at latitudes much above 75 degrees north and south on the sunlit side and 70 degrees on the dark side of the earth.

The first indication that the trapped radiation consisted of two ionized regions was provided by data from Pioneer III and IV.[98] Explorer VI[99] provided data in these two regions over a period of time, and confirmed the relative stability of the inner zone and the large variation of the outer zone. Recent data indicate that these two zones may not be as clearly separated as originally thought. The terms, "inner belt" and "outer belt," are still used, however.

The inner Van Allen Belt consists primarily of high energy protons with a peak intensity occurring on the geomagnetic equator at an altitude of 3600 km (Figure A-1a). These flux values should be correct to within a factor of 2. The peak flux of protons with energies greater than 30 Mev is 3.5×10^4 protons per square cm per second. The stability of this zone is such that about one year is required for the flux to change by a factor of 3.

Recent data[100] show that the outer belt has not only a large electron flux, but also a comparable low energy proton flux (Figure A-1b and A-1c). The peak electron intensity occurs at an altitude of about 16,000 km on the geomagnetic equator. This flux is for electrons with energies greater than 40 kev. In addition to these fluxes, there exists a low intensity (about 10^4 particles/cm^2-sec), high energy zone of electrons with energies greater than 1.6 Mev (Figure A-1d). These electrons range in altitude from about 2×10^3 to 4×10^4 km.

Both the low and high energy electrons of the outer belt can vary by an order of magnitude in less than 24 hours. In addition, during periods of geomagnetic storms this flux may increase or decrease by another order of magnitude. The degree of uncertainty associated with these fluxes is probably a factor of 5 or more at some of the higher altitudes.

A-3 THE ARTIFICIAL RADIATION BELT

During the last half of 1962, both the United States and Russia detonated nuclear weapons at high altitudes and thereby injected great numbers of fission-produced electrons into the earth's magnetic field.[100] (Three earlier detonations in 1958 by the United States, under the code name Argus, apparently did not inject great quantities of particles in the earth's magnetosphere.) The United States test, referred to as Starfish, occurred on July 9, 1962. It injected large numbers of high energy electrons and relatively few protons into the earth's magnetic field out to distances as great as 30,000 km at the geomagnetic equator. A belt of artificial radiation had been created that was similar to the natural Van Allen Belts, but of greater intensity.

The new belt took the shape of a thin crescent-shaped zone extending 20 degrees north and south of the magnetic equator, with its peak flux at an altitude of about 1300 km. The energy spectrum of the electrons is a fission spectrum which has resulted from the decay of fission products. In the heart of this belt, scattering and absorption by

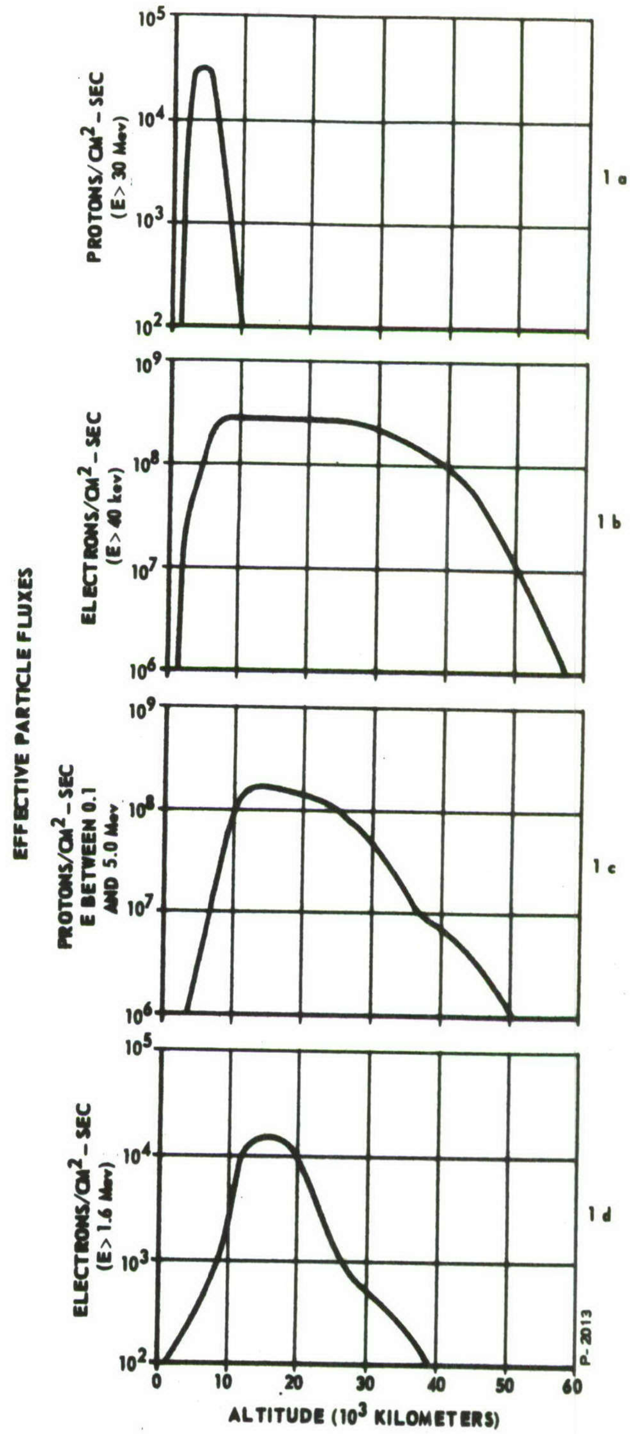


Figure A-1 - Particle Counting Rates (Flux) as a Function of Altitude

the atmosphere have caused the flux to decrease, but only by a factor of 2 every few months. The Soviet detonations were injected into the magnetic trap at a higher latitude and form a belt at a much greater altitude. Its electrons are much less energetic. Two theories have been advanced concerning the decay of the Starfish-produced flux. The first theory estimates that about 30 years will be required for the flux to decay by 10^5. Wilmot Hess of NASA, on the other hand, feels that the belts may essentially disappear when the next period of high solar activity commences and the magnetosphere undergoes large changes.(101) This will occur in the next four to six years. These magnetic storms will change both the energy spectrum and the distribution of the electrons in the artificial belt.

How these high altitude nuclear explosions enhance the over-all Van Allen Belts is not completely understood. The intensity of the low altitude belt is fairly well defined, however. The high altitude portion of the Starfish belt is included in the radiation exposure calculations.

A-4 ASSUMPTIONS FOR EXPOSURE DOSE RATE CALCULATIONS

Calculation of the curves of exposure dose rate versus altitude within the Van Allen Belt utilizes a number of assumptions. For curves of equatorial orbits or of polar orbits, the assumptions are probably valid to an altitude of about 2400 km. The measurements made 1100 km above the earth's surface are weighted and averaged over daytime and nighttime conditions and even resolve to a degree the relative conditions of a quiet sun and an active sun. The measurements made to 5600 km (Telstar altitude peak) are probably representative of some day/night average, hence are a fair base for exposure dose estimates.

Consider the perturbations of the trapped particle fluxes as a function of altitude. The earth's magnetic north pole is at a latitude of about 75°N, but the magnetic south pole is <u>not</u> diametrically opposed. This effects a magnetic shell whose mirror points (the points at which particles are reflected) occur at different latitudes as it girdles the earth. The angle the earth's magnetic vector makes with the sun's magnetic vector varies seasonally and diurnally. In addition the earth presents to the sun a diurnal variation in the intensity of the geomagnetic field. Also, the diurnal variation of the distance to the outer boundary of the geomagnetic field is marked. This outer boundary is about 100 km thick. Inside the boundary, the magnetic field strength is usually more than 30 gammas (1×10^{-5} gauss/gamma), with fluxes of about 10^6

particles/cm^2-sec of low energy (0.1 to 5 Mev) protons and of low energy (10 to 500 kev) electrons. Outside the boundary, the field strength is about 10 gammas with the attendant particle flux from the sun. On the day-side, this boundary is about 8.5 R_e (earth radius) geocentric distance, ranging from 7 to 10 R_e. On the night-side, it is less determinable and ranges from 17 to more than 40 R_e. The extent of this day-side compression is indicated by the variable character of the outer belt and the much more stable character of the inner belt, hence the suggestion that the flux estimates may be good to an altitude of about 6400 km[19] (Figure A-2). If one could observe the geomagnetic cavity from space, on the magnetic equator and with the sun-earth vector at right angles to his line of sight (at dawn or sunset), the cavity would look somewhat like the wake around a body entering the atmosphere, but with the plasma

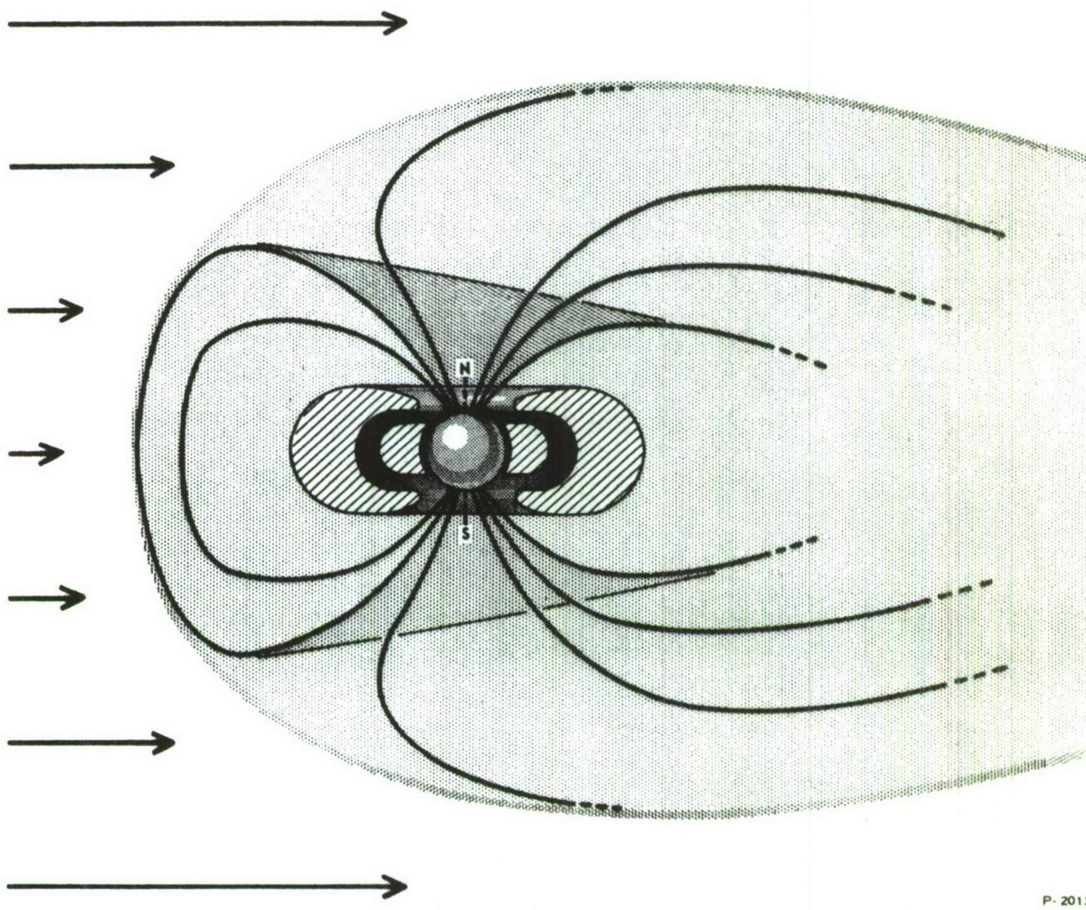


Figure A-2 - Trapped Radiation and Magnetosphere Showing Probable Distortion Due to the Solar Wind - Equatorial View

layer (neutral ionized gases) thick with respect to the size of the body[102] (Figure A-3). The lines of force radiating from the high latitudes do not rotate with the earth but are continually forced to the night-side where they contrarotate. Looking now from the polar axis, one would see a distorted raindrop shape, these high-latitude lines of force showing a magnetic "viscosity" and being disposed more toward the dawn-side of the earth (Figure A-4).[103]

The gross features of these temporal-asymmetric characteristics occur in times long with respect to the interval between mirroring and even with respect to drift time around the earth. However, the shear forces due to the solar wind (low energy protons from the sun) flowing around the cavity and the high-latitude line of force viscosity certainly must have accelerative (and decelerative) effects on the particles trapped in the outer region.

The angle which the sun-earth vector makes with geomagnetic equatorial curve (not in a plane) at northern hemisphere summer is about 6 degrees for about 12 hours; but as midnight approaches the "Capetown anomaly," this angle changes from 6 degrees to 30 degrees in six hours. This means that a certain point in the geomagnetic field at 10 R_e is moving about 1.3 km/sec with respect to its projection on the sun-earth vector. One can nearly believe the similarity to a ballistic wake previously alleged when one considers this 30 degree angle. However, the magnetic pressures bend the field so that the 30 degrees is not attained. This flailing magnetic field could be a trapping or loss mechanism or an accelerative (±) mechanism.

Now consider briefly how particle energy affects trapping. The radius of the spiral about lines of magnetic force of a low energy electron is small enough to keep high-latitude, hence high-altitude, electrons from being lost in the turbulent boundary regions even with the weak magnetic field. This radius in a strong magnetic field is small enough to keep low-latitude, hence low-altitude, electrons from being lost in the denser atmosphere. Thus, the spiral axis may approach dense regions more closely. This explains the presence of electrons in large numbers near the atmospheric bounds and the turbulent boundary. Also, this is why the spectrum is most energetic and why the intensity is greatest at intermediate altitudes (latitudes) closer to the inner bound.

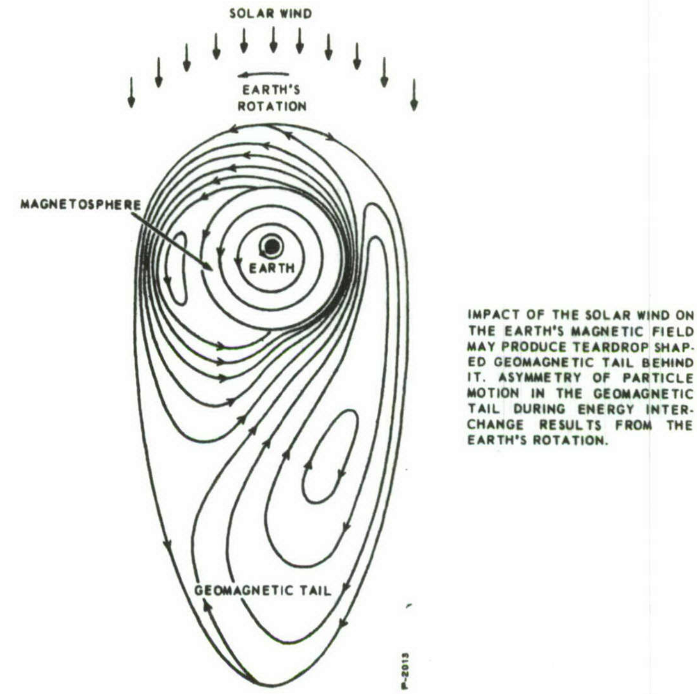
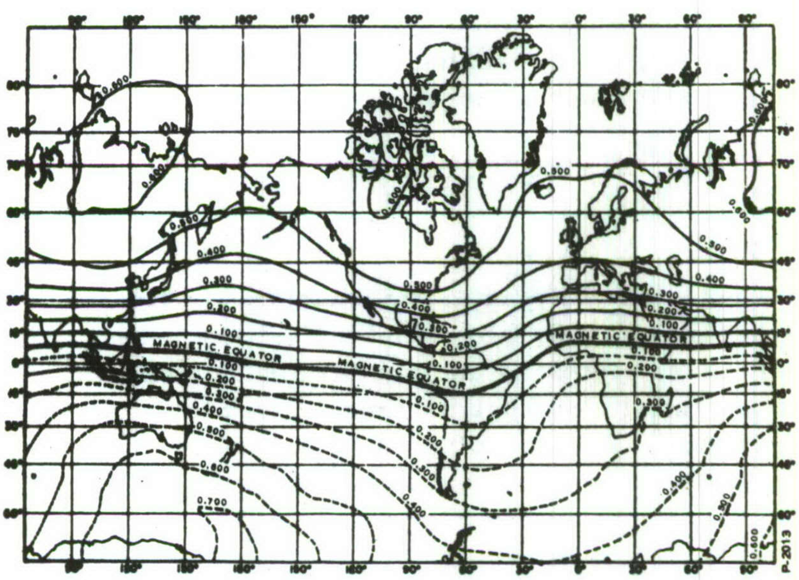


Figure A-3 - Trapped Radiation and the Magnetosphere Showing Probable Distortion Due to the Solar Wind - Polar View



FULL LINES DESIGNATE THE VERTICAL INTENSITY OVER AREAS OF POSITIVE DIP; DASHED LINES, AREAS OF NEGATIVE DIP.

Figure A-4 - Vertical Intensity Z of the Earth's Magnetic Field (in Gauss)

Since the radius of the spiral of a low energy proton is much greater than that of an equally energetic electron, the axis of its spiral may not approach the bounds as closely. The proton is less sensitive to atmosphere than is the electron, so its peak is at a much lower altitude (latitude).

In addition to the loss mechanisms of the atmospheric and turbulent bounds, the Capetown anomaly at 0 degree longitude and 45 degrees S latitude causes the mirror points at an average location of 15 degrees N and S to leak at this geographical location. This may explain the broad peaked structure seen in Figure A-1b and A-1c and also the sharply peaked intensity profile of protons in Figure A-1a.

One may recall that the three Argus shots were made at this location to get the most trapping, albeit transient, from the low loft altitude the United States could attain in 1958. The Starfish detonation was into the magnetic shell, which includes the Capetown anomaly in its mirror points, so that many of the particles produced by this shot will not be trapped.

In summary, reduction of data from Injuns I and III, Explorers X, XII, XIV, and XV, OSO 1, and subsequent scientific satellites and probes, should result in a clearer but more complex model of the trapped radiation. One has the feeling that the intensity, a function of geocentric distance, latitude, longitude, time, season, solar activity, type and energy of particles, may never be presented clearly. Perhaps the confidence in exposure rate calculations will never be comfortable.

A-5 INTERACTION OF PROTONS AND ELECTRONS WITH MATTER

A-5.1 Electrons

There are two primary mechanisms of interaction for electrons with energies up to 1 or 2 Mev. The first interaction of concern is between these electrons and orbital electrons of the atoms they meet, where the orbital electrons become excited or leave the parent atom; i.e., ionization. The loss of energy, and hence the penetration of the impinging electrons into matter, is regulated by this interaction. The range-energy relationship for monoenergetic electrons in aluminum[104] is shown in Figure A-5.

A small percentage of these electrons may interact by being accelerated by the electric field of the nucleus of an atom, thus emitting a photon during the process with energies up to that of the electron. These photons, referred to as bremsstrahlung (braking radiation) are extremely difficult to shield against and can cause damage identical to gamma ray damage.

A-5.2 Protons

Protons originating in the Van Allen Belt are likely to possess rather high energies. The primary mechanism by which these protons lose their energy is through collisions with atomic electrons.

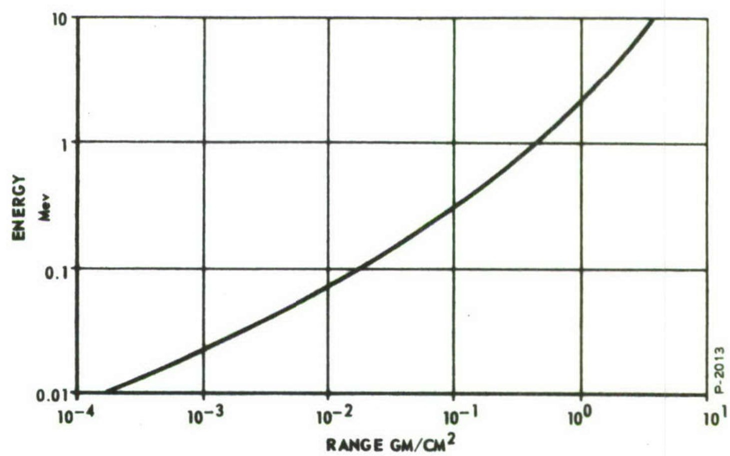


Figure A-5 - Range Energy for Monoenergetic Electrons in Aluminum

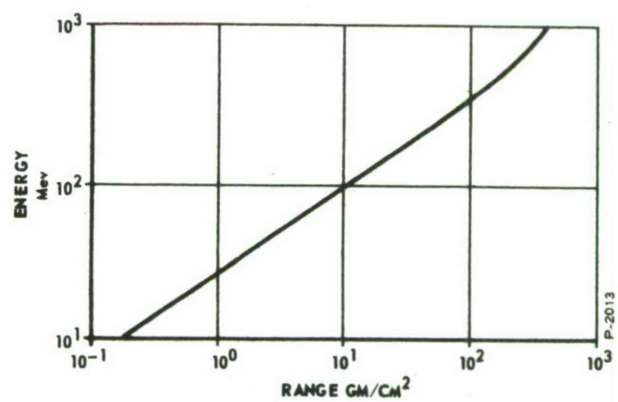


Figure A-6 - Range Energy for Monoenergetic Protons in Aluminum

The production of bremsstrahlung is improbable for the high energy protons under consideration. The collisions of protons in matter are similar to those ionizations considered for the electrons, and the proton penetration in matter is controlled by this process. Proton ranges in aluminum[105] are presented in Figure A-6. All of the interactions considered, in which protons and electrons lose energy, result in ionization in materials. In fact, less than 0.2 percent of these particles produce displacements in materials. The resulting damage in materials (primarily organics) due to ionization manifests itself as cross linking, scission, polymerization, and depolymerization. In addition, surface damage to transistors has been attributed to ionizing radiation.

A-6 CALCULATION OF EXPOSURE DOSE RATES

The exposure dose rate due to protons and electrons at a certain place (in this case air) is a measure of the ability of the radiation to produce ionization per unit time. Thus, on the basis of similar manifestations, the damaging effects to materials and components produced by interaction with electrons or protons can be compared and correlated with available damage information.

Two cases of Van Allen exposure dose rates are considered:

(1) the ionizing exposure dose which the outer surface of a satellite would receive as a function of altitude in an equatorial orbit, and

(2) the ionizing exposure dose through 1 gram per square cm (0.37 cm thickness) of aluminum for the same orbit.

For purposes of calculating exposure dose rates for both protons and electrons, the spectra of these particle fluxes were not used. Instead, the proton calculations were based on: (a) proton energies greater than 30 Mev, and (b) protons having energies from 0.1 to 5.0 Mev (3 Mev average). Likewise, the electron exposure calculations used two groups: the first with electron energies greater than 40 kev and the second with energies greater than 1.6 Mev.

The specific ionization for both the electrons and protons was computed from the following relation:[106]

$$\text{rads/hr per unit flux} = k\frac{dE}{dX} ,$$

where dE/dX is the particle energy loss in a given material in $Mev/g/cm^2$, which is obtained from appropriate tables.[107] The conversion factor k includes the following relationships:

$$1 \text{ Mev} = 1.6 \times 10^{-6} \text{ ergs}$$
$$100 \text{ ergs/g} = 1 \text{ rad.}$$

Since the unit flux is given in $particles/cm^2/sec$, k must also include the factor for converting the units of time:

$$k = \frac{1 \text{ particle}}{cm^2 - sec} \times \frac{1.6 \times 10^{-6} \text{ ergs}}{\text{Mev}} \times \frac{1 \text{ rad}}{10^2 \text{ ergs/g}} \times \frac{3.6 \times 10^3 \text{ sec}}{\text{hour}}$$

$$= 5.75 \times 10^{-5} \frac{\text{rad-g}}{cm^2\text{-Mev-hour}}$$

This calculation was used for both the surface exposure dose and the shielded exposure dose.

It was indicated in subsection A-5.1 that when electrons are slowed down in material, bremsstrahlung may result. The fraction of the electron energy converted to bremsstrahlung is estimated by:[108]

$$I = K Z E^2 ,$$

where I is the intensity of the energy converted, K is a constant determined by the energy of the incident electron, Z is the atomic number of the stopping material, and E is the incident electron energy in Mev. This expression is valid for electrons with energies up to 2.5 Mev.

Calculations for the shielded and unshielded case showed that the bremsstrahlung contribution to the exposure doses was negligible.

The results of calculations of the ionizing radiation exposure rates as a function of altitude on the geomagnetic equator are shown in Figure A-7. The top curve, which is essentially the exposure to a satellite surface, shows a peak rate of 9×10^5 rads/hr at an altitude from 1×10^4 and 2×10^4 kilometers.

The lower curve is based in part on calculation and part on the ionizing exposures measured behind comparable satellite shielding. Note that the peak exposure dose in this case occurs at an altitude of 2×10^3 to 10×10^3 kilometers, which exactly corresponds to the high